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Geotechnical Characterisation of Christchurch Strong Motion Stations

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Abstract

This report presents an overview of the soil profile characteristics at a number of strong motion station (SMS) sites in Christchurch and its surrounds. An extensive database of ground motion records has been captured by the SMS network in the Canterbury region during the Canterbury earthquake sequence. However in order to comprehensively understand the ground motions recorded at these sites and to be able to relate these motions to other locations, a detailed understanding of the shallow geotechnical profile at each SMS is required.

The original NZS1170.5 (SNZ 2004) site subsoil classifications for each SMS site is based on regional geological information and well logs located at varying distances from the site. Given the variability of Christchurch soils, more detailed investigations are required in close vicinity to each SMS to better understand stratigraphy and soil properties, which are important in seismic site response. In this regard, CPT, SPT and borehole data, shear wave velocity (V_s) profiles, and horizontal to vertical spectral ratio measurements (H/V) in close vicinity to the SMS were used to develop representative soil profiles at each site.

NZS1170.5 (SNZ 2004) site subsoil classifications were updated using V_s and SPT N_{60} criteria. Site class E boundaries were treated as a sliding scale rather than as a discrete boundary to account for locations with similar site effects potential, an approach which was shown to result in a better delineation between the site classes. SPT N_{60} values often indicate a stiffer site class than the V_s data for softer soil sites, highlighting the disparity between the two site investigation techniques. Both SPT N_{60} and V_s based site classes did not always agree with the original site classifications. This emphasises the importance of having detailed site-specific information at SMS locations in order to properly classify them. Furthermore, additional studies are required to harmonize site classification based on SPT N_{60} and V_s.

Liquefaction triggering assessments were carried out for the Darfield and Christchurch earthquakes, and compared against observed liquefaction surface manifestations and ground motions characteristics at each SMS. In general, the characteristics of the recorded ground motions at each site correlate well with the triggering analyses. However, at sites that likely liquefied at depth (as indicated by triggering analyses and/or inferred from the characteristics of the recorded surface acceleration time series), the presence of a non-liquefiable crust layer at many of the SMS locations prevented the manifestation of any surface effects.

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1 Introduction

This report presents updated soil profile classifications for a selection of strong motion stations (SMS) in the vicinity of Christchurch based on recent site-specific geotechnical investigations. Cone penetrometer testing (CPT), boreholes and standard penetration testing (SPT), surface shear wave velocity (V_s) profiling, and horizontal to vertical spectral ratio (H/V) calculations were performed at SMSs in Christchurch City, Kaiapoi and Lyttelton. This report focusses on the SMSs installed prior to the 4 September 2010 Darfield earthquake, as these recorded the majority of the major earthquakes in the Canterbury earthquake sequence.

The main aim of this research was to develop representative soil profiles based on site-specific geotechnical investigations and subsequently re-assess the NZS1170.5 site subsoil classes (referred to as site classes in the remainder of this report).

Additionally, liquefaction triggering assessments were carried out using CPT sounding data following the methodology outlined in Youd et al. (2001). These assessments were compared against the observed liquefaction surface manifestations and the characteristics of the ground motions recorded at each SMS during the Darfield and Christchurch earthquakes.

1.1 Christchurch Strong Motions Station Network

Prior to the 2010 Darfield earthquake, the city of Christchurch was instrumented with a large network of strong motion stations. Within Christchurch there were seven SMSs as part of the National Strong Motion Network and nine as part of Canterbury regional strong motion network (Avery et al. 2004). Additionally, there were SMSs located in both Lyttelton (LPCC) and Kaiapoi (KPOC), all combined as part of the GeoNet project (GNS Science 2013). This network of SMSs recorded a vast database of strong ground motions during the Canterbury earthquake sequence. The National Strong Motion Network (NSMN) uses Kinemetrics Etna strong motion accelerographs, and the Canterbury regional strong motion network (CanNet) uses CSI CUSP3B strong motion accelerographs.

Between the 22 February 2011 Christchurch earthquake and February 2012, nine additional SMSs were installed in the Christchurch area as part of the National Strong Motion Network. Of the nine new stations, four are located on rock sites, whereas previously only two SMSs had been located on a rock site in this region. Since February 2012, additional permanent SMSs have been installed, increasing the number of SMSs to 35 in Christchurch, Lyttelton and Kaiapoi combined.

This research focuses on the SMSs installed prior to the Darfield earthquake. The SMS study sites, their network, and their coordinates are summarised in Table 1. An overview of the SMS study sites in Christchurch and Lyttelton is presented in Figure 1, while the SMS in Kaiapoi is outside the boundaries of this figure. The SMSs characterised in this study are indicated by red circles with labels in this figure, with other SMSs locations shown as black circles. This report focusses on this reduced group of SMSs as they were installed prior to the 4 September 2010 Darfield earthquake, and therefore recorded the majority of the major earthquakes in the Canterbury earthquake sequence.

The other SMSs in this region were not considered in this study because they recorded a small number of events, and also project time and budget limitations. However, future investigations are essential in order to classify the newer SMSs locations and to understand future recorded ground motions.

Table 1 Strong motion station details and coordinates (WGS 84)

Station Name	Code	Network	Latitude	Longitude
Canterbury Aero Club	CACS	NSMN	-43.48316539	172.5300139
Christchurch Botanical Gardens	CBGS	NSMN	-43.52933938	172.6198776
Christchurch Cathedral College	CCCC	CanNet	-43.5380850	172.6474270
Christchurch Hospital	CHHC	CanNet	-43.53592591	172.6275195
Cashmere High School	CMHS	NSMN	-43.56561744	172.6241694
Hulverstone Drive Pumping Station	HPSC	CanNet	-43.50157144	172.7021909
Heathcote Valley Primary School	HVSC	CanNet	-43.57977835	172.7094230
Kaiapoi North School	KPOC	CanNet	-43.37646016	172.6637603
Lyttelton Port	LPCC	CanNet	-43.60784334	172.7247726
New Brighton Library	NBLC	CanNet	-43.50685883	172.7313538
North New Brighton School	NNBS	NSMN	-43.49541878	172.7179969
Papanui High School	PPHS	NSMN	-43.49284238	172.6069135
Pages Road Pumping Station	PRPC	CanNet	-43.52580347	172.6827633
Christchurch Resthaven	REHS	NSMN	-43.52194513	172.6351501
Riccarton High School	RHSC	CanNet	-43.5361720	172.5644040
Shirley Library	SHLC	CanNet	-43.50533475	172.6633938
Styx Mill Transfer Station	SMTC	CanNet	-43.46752930	172.6138611

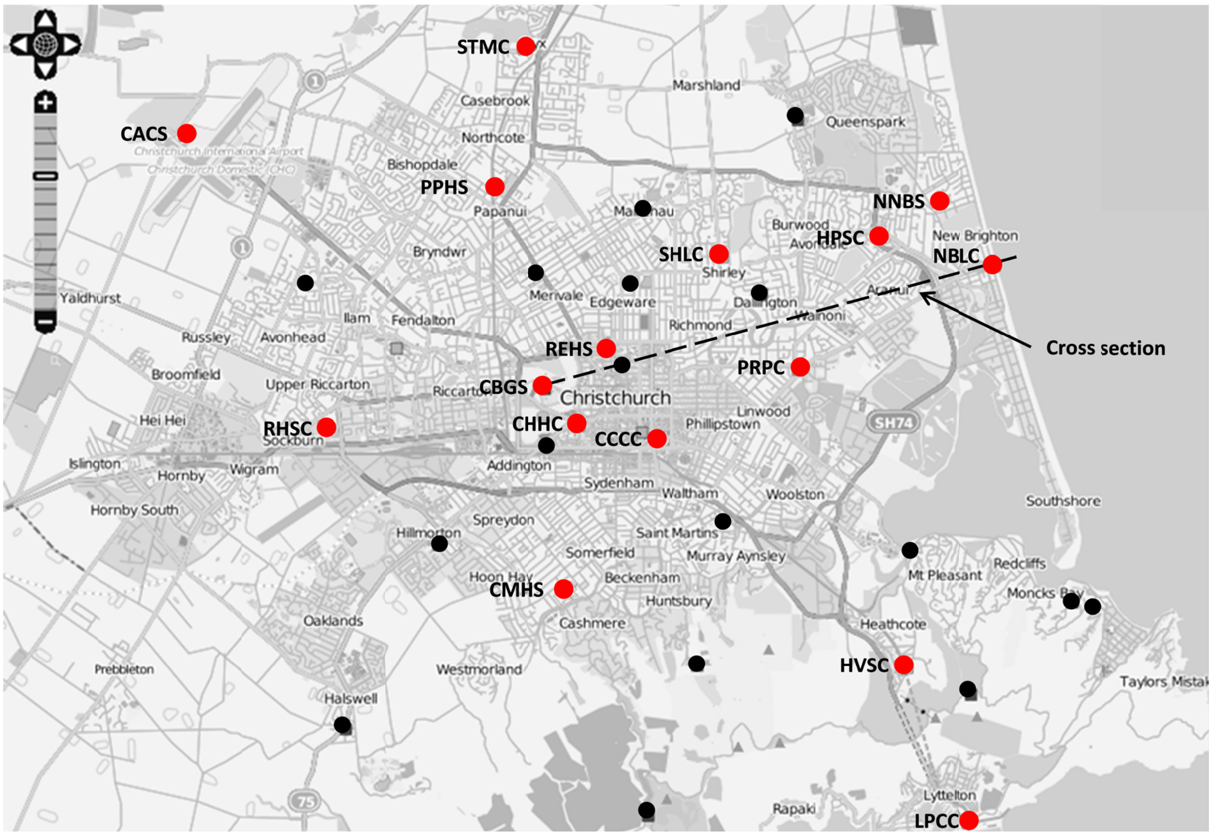

Figure 1 Christchurch and Lyttelton Strong Motion Station Network (adapted from GeoNet (GNS Science 2013))

2 Methodology

2.1 Geotechnical Site Investigation

Prior to 2011, little information regarding the subsurface geotechnical characteristics of the strong motion station locations in and around Christchurch was available. As noted in Cousins & McVerry (2010), the soil profiles and site classes at each SMS were assumed from well logs and regional geological knowledge. An overview of the site classifications based on this prior knowledge is presented in Section 3.3, and a more detailed summary of site investigations at each SMS are presented on a site-by-site basis in Section 4.

2.1.1 CPT, Borehole and SPT Testing

Initially, existing CPT, borehole and SPT data in the vicinity of each SMS were collected from available sources (Canterbury Geotechnical Database 2013). At locations with a paucity of data, an additional program of subsurface site investigations was carried out using CPT and borehole methods where appropriate. A complete collation of the site investigations that were carried out at each SMS location is presented in Appendix C.

At each site, CPT data was used to calculate the soil behaviour type index (I_c) as a function of depth, to enable qualitative comparisons with the borehole log data (Robertson & Wride 1998). The I_c ranges and their inferred soil types are outlined in Table 2.

Table 2 Soil behaviour type index ranges and inferred soil types (Robertson & Wride 1998)

Soil Behaviour Type Index, I_c	Inferred Soil Type
$I_c < 1.31$	Gravelly sand to dense sand
$1.31 < I_c < 2.05$	Sands: clean sand to silty sand
$2.05 < I_c < 2.60$	Sand mixtures: silty sand to sandy silt
$2.60 < I_c < 2.95$	Silt mixtures: clayey silt to silty clay
$2.95 < I_c < 3.60$	Clays: silty clay to clay
$I_c > 3.60$	Organic soils: peats

Because the interpretation of sites classes in NZS1170.5 is based on SPT data for cohesionless soils, CPT data was also converted to an equivalent SPT N_{60} value using the approach from Lunne et al. (1997):

$$\frac{(q_t / p_a)}{N_{60}} = 8.5\left(1 - \frac{I_c}{4.6}\right) \tag{1}$$

where q_t is the corrected cone resistance, p_a is atmospheric pressure, and I_c is the soil behaviour type index. Additionally, because the energy efficiency of the SPT hammers used in investigations were variable (60-99%), and in most cases significantly higher than the 60% benchmark, SPT N_{60} values rather than raw SPT N values have been used for the site classifications in this report.

2.1.2 Shear Wave Velocity Profiles

Shear wave profiles presented herein were developed using dispersion data from the study summarised in Wood et al. (2011) and additional surface wave testing. A combination of active-source and passive-source surface wave techniques were used to resolve the shear stiffness and layering beneath each SMS. Active-source methods included a combination of the Spectral Analysis of Surface Waves (SASW) (Nazarian & Stokoe 1984, Stokoe et al. 1994) and the Multi-channel Analysis of Surface Waves (MASW) (Park et al. 1999), while passive-source methods included a combination of linear (Louie 2001, Park & Miller 2008) and 2D microtremor array methods (MAM) (Tokimatsu et al. 1992, Okada 2003). The testing methods and setup parameters used at each SMS location are outlined in Appendix C.

Linear array (1D) testing employed a receiver array composed of 24, 4.5-Hz geophones with an equal spacing (dx) between receivers. For active-source testing, a 5.4 kg sledgehammer was used to generate surface wave energy by striking an aluminium plate. At sites with surface soil conditions, a P-wave refraction survey was performed using the linear array (P-wave refraction could not be conducted at sites with asphalt or concrete at the surface). These measurements were used to determine the depth to saturation (ground water table) at each station for input into the surface wave inversion and future liquefaction analyses. For refraction testing, five hammer blows (shots) located one receiver spacing in front of the first receiver were stacked to increase the signal-to-noise ratio. At this same source location, SASW data was also collected using select pairs of geophones within the linear array. Typical receiver spacing's included 1dx, 2dx, 3dx, 4dx, 6dx, 8dx, 10dx and 12dx. These pairs of receivers were always chosen to maintain the source-to-first receiver distance equal to the first-to-second receiver distance, as is typical in SASW testing (Stokoe et al. 1994). Following the SASW data collection, MASW testing was performed using three separate source locations from the first receiver in the array. As with the P-wave refraction, at least five sledgehammer blows were average together at each source location to increase the signal-to-noise ratio.

Linear array passive surface wave testing (i.e., ReMi as described in Louie (2001)) was conducted using the same array used for active testing. During passive testing, a total of 10, 32-s long noise signals were recorded. The linear array was then converted into a 2D array by rotating 12 of the 24 geophones 90 degrees. The 2D passive array has several advantages over a linear passive array, the most important of which is the ability to resolve the direction of surface wave propagation. The lack of directional information when using a linear passive array can lead to significant errors in velocity profiles under certain circumstances and caution should be exercised when using this method without other corroborating active or 2D passive methods (Cox & Beekman 2011).

The SASW data was analysed using the phase unwrapping method to determine the individual dispersion curves from each receiver spacing. The individual dispersion curves were then combined to form a composite dispersion curve over the frequencies/wavelengths of interest. The MASW data was analysed using the frequency domain beamformer method (Zywicki 1999). For each source offset, a dispersion curve was generated by picking the maximum spectral peak in the frequency/wavenumber domain. The linear array passive data was analysed using the two-dimensional slowness-frequency (p-f) transform in the software SeisOpt ReMi (Optim 2006). The 2D MAM data was analysed using the 2D frequency domain beamformer method (Zywicki 1999).

Further information about the general surface wave processing methods can be found in Cox and Wood (2011).

Once the surface wave dispersion trends from each method were obtained, a mixed-method composite dispersion curve was generated by combining the dispersion data from each active and passive surface wave method. The dispersion data was then divided into 30 wavelength bins using a log distribution. The mean phase velocity and associated standard deviation was then calculated for each bin, resulting in an experimental dispersion curve with associated uncertainty. The shear wave velocity profile was then determined by fitting a 3D theoretical solution to the mean experimental dispersion curve using the software WinSASW. Layering characteristics at each site from the subsurface investigations were used to help constrain the layering of the shear wave velocity profile. The 3D solution uses the superposed mode dynamic stiffness matrix method to solve for the surface displacements generated by all Rayleigh wave modes and body waves (Joh 1996). The solution is the most appropriate solution for SASW and can also be used to account for the smearing/superposition of modes that can exist in MASW dispersion data at longer wavelengths due to a lack of spatial resolution. The shear wave velocity profiles obtained from the inversions for each site were limited to the maximum experimental wavelength divided by two (i.e., $\lambda_{max}/2$).

Note that V_s estimates from surface wave methods are considered accurate to within 10% (Wood et al. 2011), with this taken into account in the application of a site class to each SMS location.

2.1.3 Horizontal to Vertical Spectral Ratio

To estimate the site period (T) of each SMS, the ratios of the horizontal-to-vertical Fourier amplitude spectra (FAS) of the recorded ambient noise and earthquake-induced ground motions were used (i.e., H/V spectral ratios). The premise of the H/V spectral ratio approach is that the vertical component of surface ground motion reflects only source and path effects and is not significantly influenced by site effects (due to a large P- to S wave velocity ratio). In contrast, the horizontal component of ground surface motions reflects source, path, and site effects. As a result, the H/V spectral ratios primarily reflect site effects, similar to the transfer function, and the source and path effects largely normalize out (Nakamura 1989, Field et al. 1990, Lermo & Chavez-Garcia 1993, 1994, Field & Jacob 1993, Field et al. 1995, Konno & Ohmachi 1998).

Details of the H/V spectral ratios developed using earthquake-induced ground motions are summarised in Wood et al. (2011). H/V spectral ratios developed using ambient noise recordings were carried out at each SMS location using a Nanometrics Trillium compact 120 second broadband seismometer. At least one hour of ambient noise was recorded at each site and processed using the software Geopsy. The squared average of the horizontal components of noise was used, and a Konno & Ohmachi (1998) smoothing function was applied to the data with a smoothing constant of 40. A range of time window sizes were compared against one another to identify their influence on the data processing and develop appropriate H/V spectral ratio values.

2.2 NZS1170.5 Site Classes

NZ1170.5 (SNZ 2004) uses a combination of undrained shear strength (s_u), SPT N, V_s, and site period (T) to define site classes. In this report, all SMSs apart from LPCC have greater than 3 m of soil above bedrock at their location, which is the cutoff between site class B – rock, and site class C – shallow soil. Therefore, the remaining SMS are classified as either site class C – shallow soil, site class D – deep or soft soil, or site class E – very soft soil. A summary of the site class is provided in Table 3.

Locations are defined as site class E if they have greater than 10 m of low strength material with s_u<12.5 kPa, SPT N < 6 blws/0.3 m, or V_s < 150 m/s. Sites outside these limits will be either site class C or D, and can be differentiated using two approaches. Firstly, if the low amplitude natural period (or site period) is less than or equal to T=0.6 seconds, the site can be classified as site class C. The natural period of a soil deposit over bedrock is theoretically calculated as four times the shear wave travel time from bedrock to the surface. Natural period can be estimated from a V_s profile that extends down to bedrock (or another significant impedance contrast) or from direct horizontal-to-vertical spectral ratio (H/V) measurements. Secondly, maximum depth limits are defined for a range of representative s_u and SPT N soil profiles to delineate the site class C and D boundary in Table 3.2 of NZS1170.5. The maximum depth for very dense cohesionless soils is 60 m, and the maximum depth of gravels is 100 m. Utilizing natural period to define site class is the preferred of the two approaches.

Table 3 Summary of the NZS1170.5 site class guidelines (SNZ 2004)

3.1.3.4 *Class C – Shallow soil sites* Class C is defined as sites where: (a) They are not class A , class B or class E sites; and (b) The low amplitude natural period is less than or equal to 0.6 s; or (c) Depths of soil do not exceed those listed in Table 3.2. The low amplitude natural period may be estimated from four times the shear-wave travel time from the surface to rock, be estimated from Nakamura ratios or from recorded earthquake motions, or be evaluated in accordance with Clause 3.1.3.7 for sites with layered subsoil, according to the hierarchy of methods given in Clause 3.1.3.1. **3.1.3.5** *Class D – Deep or soft soil sites* Class D is defined as sites: (a) That are not class A , class B or class E sites; and (b) Where low-amplitude natural period is greater than 0.6 s; or (c) With depths of soils exceeding those listed in Table 3.2; or (d) Underlain by less than 10 m of soils with an undrained shear-strength less than 12.5 kPa or soils with SPT N-values less than 6. The low amplitude natural period may be determined in accordance with Clause 3.1.3.4. **3.1.3.6** *Class E – Very soft soil sites* Class E is defined as sites with: (a) More than 10 m of very soft soils with undrained shear strength less than 12.5 kPa; or (b) More than 10 m of soils with SPT N-values less than 6; or (c) More than 10 m depth of soils with shear-wave velocities of 150 m/s or less; or (d) More than 10 m combined depth of soils with properties as described in (a), (b) and (c) above.

The natural period at each SMS location is estimated using three approaches in this paper. The first approach uses the V_s profile at each SMS to calculate the average shear wave velocity for the profile (V_{Savg}) down to the top of bedrock, or to the maximum depth that V_s was characterized when bedrock was not encountered. V_{Savg} is calculated by:

$$V_{Savg} = \frac{\sum_i h_i}{\sum_i \frac{h_i}{V_{si}}} \tag{2}$$

where h_i is the thickness of layer i, and V_{si} is the shear wave velocity of layer i. The fundamental period (T) of the uniform profile is equal to:

$$T = \frac{4H}{V_{Savg}} \tag{3}$$

where H is the overall thickness of the profile. At sites where bedrock is encountered this will give the overall soil profile natural period.

If bedrock is not encountered these equations provide a lower bound estimate of the natural period of the soil profile over this reduced depth.

The second approach uses the H/V spectral ratios from recorded earthquake motions summarized in Wood et al. (2011). The final approach uses the H/V spectral ratios from ambient noise recordings outlined in the previous section. Other possible approaches for estimating natural period, such as assuming a visco-elastic soil profile, are not presented here.

Choice of the appropriate site class at each SMS location has been made based on interpretation and engineering judgment, and not simply the strict application of site class boundaries. In particular, this applies to the limits between site class D and E. Site class E is defined as a site with 10 m or more of soil with the following characteristics: $s_u \leq 12.5$ kPa, SPT $N \leq 6$ blws/0.3 m, or $V_s \leq 150$ m/s. For SMS locations where soil conditions are on the borderline of site class D and E, a dual classification D/E has been applied.

Clearly there are combinations of depth and soil properties that do not strictly align with the site class E criteria, but for which similar site effects are likely. Therefore, the site class E boundaries are treated more as a sliding scale than as a discrete boundary (i.e., a profile with 15 m of 160 m/s soil or a profile with 8 m of 120 m/s soil should be considered equivalent to a profile with 10 m of 150 m/s soil). In cases where the soil layering does not strictly meet the site class E criteria, but possesses similar site effects potential, a site classification E* has been applied to the site. These cases can be broadly defined as follows:

- Profiles with less than 10 m of soil with strength/stiffness properties less than the site class E limiting criteria, where the combination of the percentage reduction in depth and soil strength/stiffness indicates that site class E* may be appropriate (eg. the HPSC SMS). A limit of a 20% reduction in the thickness criteria has been used in these cases.
- Profiles with greater than 10 m of soil with strength/stiffness properties slightly greater than the site class E limiting criteria, where the combination of the percentage increase in depth

and soil strength/stiffness properties indicates that site class E* may be appropriate (eg. the PRPC SMS). A limit of a 20% increase in the soil property criteria has been used in these cases.

2.3 Liquefaction Triggering Assessment

Using the soil profile data, an assessment of liquefaction triggering was carried out for both the M_w7.1 Darfield and M_w6.2 Christchurch earthquake ground motions. These events were chosen as they generally produced the strongest ground motions at the majority of the SMSs, and did not occur in close succession to another large event (which was the case for the 13 June 2011 and 23 December 2011 earthquakes). The recorded geometric mean of the ground motions at each SMS, summarised in Table 4, were used in this analysis. Soil total unit weight was estimated using the approach outlined in Robertson & Cabal (2010). The water table depth measured during subsurface geotechnical investigations was used for both the Darfield and Christchurch earthquakes. This depth was modified in each calculation to determine the effect on the liquefaction triggering calculations, which was not significant in any of the cases.

The cyclic stress ratios (CSR) for the Darfield and Christchurch earthquakes were calculated using the methodology outlined in Youd et al. (2001). The CSR values were scaled to a value representative of a M_W7.5 earthquake ($CSR_{7.5}$) using the average of the recommended range of the magnitude scaling factors (MSFs) recommended by Youd et al. (2001).

Table 4 Geometric mean horizontal peak ground acceleration of SMS accelerograms (Geonet 2013)

Station Name	Code	Darfield Earthquake PGA (g)	Christchurch EQ PGA (g)
Canterbury Aero Club	CACS	0.20	0.21
Christchurch Botanical Gardens	CBGS	0.16	0.50
Christchurch Cathedral College	CCCC	0.22	0.43
Christchurch Hospital	CHHC	0.17	0.37
Cashmere High School	CMHS	0.24	0.37
Hulverstone Dr Pumping Station	HPSC	0.15	0.22
Heathcote Valley School	HVSC	0.61	1.41
Kaiapoi North School	KPOC	0.34	0.20
Lyttelton Port	LPCC	0.29	0.92
New Brighton Library	NBLC	-	-
North New Brighton School	NNBS	0.21	0.67
Papanui High School	PPHS	0.22	0.21
Pages Rd Pumping Station	PRPC	0.21	0.63
Christchurch Resthaven	REHS	0.25	0.52
Riccarton High School	RHSC	0.21	0.28
Shirley Library	SHLC	0.18	0.33
Styx Mill Transfer Station	SMTC	0.18	0.16

The cyclic resistance ratio ($CRR_{7.5}$) using the CPT profiles was calculated following the procedure outlined in Youd et al. (2001) for each site investigation technique. The $CRR_{7.5}$ value was modified using the overburden correction factor K_σ (Hynes and Olsen 1999), allowing the $CSR_{7.5}$ for the two earthquakes and the $CRR_{7.5}$ for each site investigation technique to be compared directly.

Summaries of the liquefaction triggering calculations for each earthquake are presented in Appendix B. The CPT tip resistance (q_c), soil behaviour type index (I_c), relative density (D_r) and factor of safety against liquefaction (FOS) are summarised in each figure. Following the guidelines of Youd et al. (2001), soils with an I_C>2.4 are considered non-liquefiable. Layers in which liquefaction is triggered are represented by the shaded areas between the FOS curve and a FOS=1.

These assessments were compared against the observed liquefaction surface manifestations following each earthquake and the characteristics of the ground motions recorded at each SMS. Alternative liquefaction triggering assessment methodologies for CPT, SPT and V_s data have not been summarised in this report.

3 Summary of Strong Motion Station Characteristics

This section provides a summary of the SMS characteristics developed using the methodologies outlined in the previous sections. Depth to bedrock and consistent gravels are outlined, followed by a discussion of the estimated site period developed using the procedures outlined in Section 2.2. This data is combined with the other surface and subsurface investigation details to define the NZS1170.5 site class at each SMS location based on SPT N_{60} and V_S. Finally, the average shear wave velocity to a depth of 30 m (V_{S30}) is discussed, as it is a common site classification measure used in ground motion prediction equations and other site classification methodologies.

3.1 Bedrock and Gravel Layers

An overview of the SMS within Christchurch and the near surface stratigraphy outlined in Brown & Weeber (1992) is presented in Figure 2. This indicates the locations of different soil deposits and locations where shallow gravel layers are present. Gravel layers dominate the stratigraphy in the west of the city, while in the east there are no shallow gravel layers present. Using data from site investigations, a summary of the SMS locations where bedrock was encountered and the details of gravel layering are outlined in Table 5. The subsurface stratigraphy outlined in Figure 2 compares fairly well to the data from site investigation.

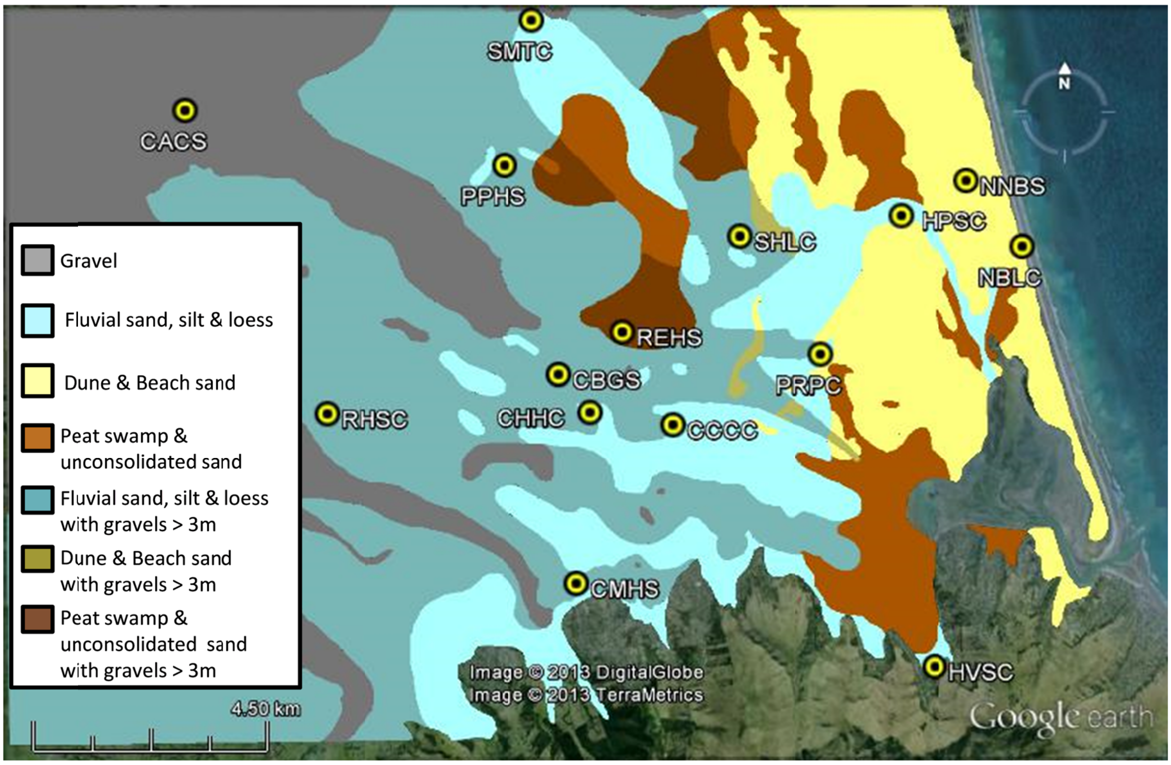

Figure 2 SMS locations with surface and near surface stratigraphy (after Brown & Weeber 1992)

Of all the sites investigated, only HVSC and LPCC (not shown in the figure below) encountered bedrock with subsurface investigations, consistent with the sites' proximity to the Port Hills. Moving out from the Port Hills, the surface geophysical investigations at CMHS, near the edge of the Port Hills, indicated the presence of bedrock at a relatively shallow depth, although this was not encountered by subsurface investigations. The rest of the SMS locations are further from the Port Hills and underlain by deep (i.e. many hundreds of metres) sedimentary deposits of interbedded gravels and fine to very fine grain sediments (Brown & Weeber 1992).

Table 5 Summary of bedrock and gravel details at each SMS location

Code	Bedrock encountered	Depth to consistent gravels (m)	Shallow gravels present
CACS	N	0	NA
CBGS	N	21	Y
CCCC	N	25	N
CHHC	N	22.5	Y
CMHS	N	13.8	Y
HPSC	N	36	N
HVSC	Y	NA	NA
KPOC	N	8.6	Y
NBLC	N	45	N
NNBS	N	41	N
PPHS	N	19	Y
PRPC	N	28	N
REHS	N	20	Y
RHSC	N	6.3	N
SHLC	N	27	Y
SMTC	N	17.9	Y

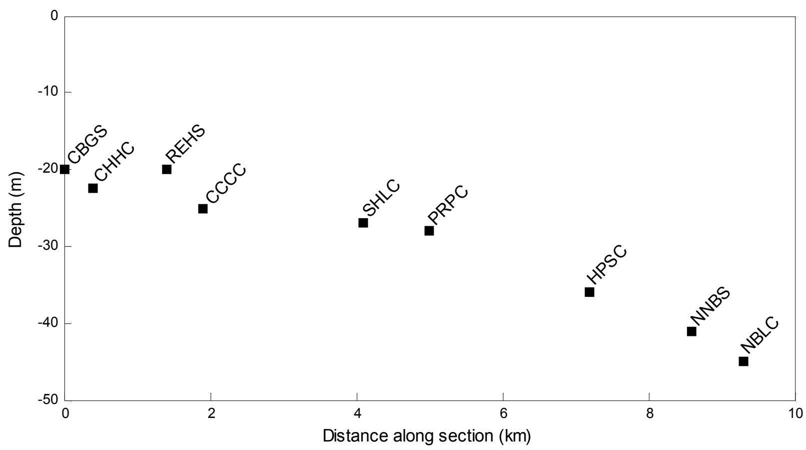

Figure 3. Cross section showing depth to Riccarton Gravels beneath Christchurch (location indicated by dashed line in Figure 1)

Another depth measure in the central and eastern region of Christchurch is the depth to the Riccarton Gravel Formation, important because it is the most suitable founding depth of deep foundation systems and is an aquifer that forms a major part of the Christchurch water supply. A summary of the depth to the consistent gravel layer beneath the city is summarised in Table 5, as is the locations where gravel layers were encountered above this consistent gravel layer. Taking a cross section of the city from CBGS to NBLC (shown by the dashed line in Figure 1), and projecting the depths to the Riccarton Gravels from the subsurface site investigations at surrounding SMSs onto this section, an overview of the depth variation beneath the central and eastern part of the city is shown in Figure 3.

The gravel creates a significant V_S contrast with the overlying looser sediments (Christchurch and Springston Formation) across much of Christchurch and is likely to result in a significant higher mode of vibration that has a much shorter period than the site period of the entire soil column down to bedrock. Many of the site periods identified using the H/V spectral ratio approach were representative of the profile over this gravel layer. Further study is warranted to determine the impacts of this higher mode of vibration on site classification.

3.2 Site Periods

The site period estimates using the approaches outlined in Section 2.2 are summarised in Table 6. The V_S data at each SMS was used to estimate the site period using the approach outlined in Section 2.2. However, as the V_S profile only extended to bedrock at HVSC and CMHS, these are the only SMSs where V_S can provide an estimate of the site period down to bedrock (shown by the shaded cells). For the remainder of the SMSs, the V_S profile was used to estimate the period of this reduced thickness to the base of the V_S profile. Additionally, for those sites where the V_S profile extended down to a gravel layer, an estimate of the site period of the soils above this V_S contrast was defined.

Table 6 Summary of site period estimates and period of reduced profile depths (seconds)

Code	From V_S profile		Ambient noise H/V		EQ H/V
	To profile base/bedrock	Above gravel	Short period	Long period	
CACS	0.35	-	-	6.33	-
CBGS	0.61	0.52	0.69	-	0.45
CCCC	0.65	0.61	0.71	2.37	0.71
CHHC	0.66	0.53	0.74	-	0.53
CMHS	0.69	0.38	0.71	-	0.72
HPSC	0.64	0.64	-	-	0.45
HVSC	0.24	-	0.27	-	0.42
KPOC	0.64	0.26	0.27	-	0.36
NBLC	0.70	0.70	-	3.75	-
NNBS	0.64	-	-	4.87	0.73
PPHS	0.63	0.34 & 0.53	0.52	5.91	-
PRPC	0.70	0.66	0.61	-	0.83
REHS	0.82	0.69	0.57	-	0.65
RHSC	0.43	0.15	-	5.2	0.35
SHLC	0.64	0.57	0.61	-	0.54
SMTC	0.54	0.43	0.54	6.25	-

The H/V spectral peaks from ambient noise recordings likely correspond to either the site period of shallow soils above gravels, the site period for the entire soil profile down to bedrock, or both. For the sites away from the Port Hills, the H/V spectral peaks from recorded earthquake motions (Wood et al. 2011) likely correspond to the site period of the soil profile above the stiff gravel layers. The estimated site period above gravels using the V_S profile generally correlated well with the short period H/V spectral peak from ambient noise methods and the H/V spectral peaks from the recorded earthquake motions.

Away from the Port Hills, the site period of each SMS will be significantly higher than the site class D threshold, as Christchurch is underlain by many hundred metres of sedimentary deposits. This is indicated by the long period H/V spectral peaks from ambient noise measurements at a handful of sites away from the Port Hills which were all in excess of 2.37 seconds. The CMHS SMS, only 300 m from the base of the Port Hills, had an estimated site period of approximately 0.7 seconds above rock. The next closest SMS is approximately 2.7 km from the Port Hills, which is the location with the 2.37 second spectral peak. This suggests that the remainder of sites were long period H/V spectral peaks were not identified are all likely to have site periods well in excess of the site class D limit.

Using the NZS1170.5 preferred approach, only HVSC had an estimated site period less than the T=0.6 second threshold for site class D. The rest of the SMS investigated will be either site class D or E, with the site period of the profile above bedrock at all these locations greater than 0.6 seconds.

3.3 NZS1170.5 Site Class

A summary of the NZS1170.5 site classes defined using the V_s profiles and subsoil geotechnical in-situ test data is presented in Table 7. As the LPCC SMS is located on rock, no additional site investigations were carried out at this location.

Based on the measured N_{60} values and/or equivalent N_{60} values from CPT soundings, four sites (HPSC, KPOC, NNBS, PRPC) in Table 7 shifted to a stiffer site class (i.e. a shift from site class E to D) compared to the original assumptions. Two sites that were originally assumed to be site class E have been given a classification of site class E* (PPHS, REHS). Finally, two sites that had a dual classification prior to site specific testing (SHLC, SMTC) were reclassified as the stiffer of these site classes (site class D). If raw SPT N values were used to classify these sites rather than SPT N_{60}, the same site classes would have been defined. However, it must again be stressed that given the variability in SPT hammer efficiency, the use SPT N_{60} is a more consistent approach.

Based on V_s, only 9 of the 17 sites shown in Table 7 in had sites classes that agreed with what had previously been assumed based on the NZS1170.5 guidelines. Of the sites that were originally assumed to be site class E, three have been given a classification of site class E* (HPSC, NNBS, PRPC) and one has been shifted to the stiffer site class D (KPOC). CBGS, CCCC and PPHS were defined as site class E, shifting from the site class D that was originally assumed. Two other sites were given a classification of site class E*, with one of these (REHS) originally designated site class D. Two sites that had a dual classification prior to site specific testing (SHLC, SMTC) were reclassified as the stiffer of these site classes (site class D).

Overall, eleven sites were given the same site class using V_s and SPT N_{60} , seven of these site class D, two site class E*, and one each of site class C and B. Five sites designated site class E* and one site class E using V_s were designated site class D using SPT N_{60}, and in these cases the SPT N_{60} values were well above the site class E boundary. Apart from the two SMS locations with a new E* classification based on SPT N_{60}, the rest of the sites were either confirmed as a site class D, or shifted from a site class E or dual classification D/E to site class D. It is these softer sites where the most significant difference between SPT N_{60} and V_s based site classes are highlighted.

The disagreement between V_s and SPT N site classification has been identified in other studies. Some potential issues may be: (1) correlating SPT N values from a generic (i.e., not regional specific) CPT relationships, and (2) using uncorrected/raw SPT N values without adjusting for overburden pressure and hammer efficiency as is typically done for liquefaction triggering analyses. Regarding potential differences in site classification obtained from SPT N, s_u and V_s, the American Association of State Highway and Transportation Officials (AASHTO) recommends "In all evaluations of site classification, the shear wave velocity should be viewed as the fundamental soil property, as this was used when conducting the original studies defining the site categories" (AASHTO 2011). This course of action obviously requires high-quality V_s measurements made by competent experts, as V_s profiles obtained from surface wave methods require a great deal of expertise and care. Clearly the decision to classify a site based on SPT N versus V_s requires further study.

Table 7 Summary of site classes based on original assumptions, SPT N_{60} and V_s

Code	Original Assumed Site Class	SPT N_{60} Site Class	V_S Site Class
CACS	D	D	D
CBGS	D	D	E
CCCC	D	D	E
CHHC	D	D	D
CMHS	D	D	D
HPSC	E	D	E*
HVSC	C	C	C
KPOC	E	D	D
LPCC	B	B	B
NBLC	U	D	E*
NNBS	E	D	E*
PPHS	D	E*	E
PRPC	E	D	E*
REHS	D	E*	E*
RHSC	D	D	D
SHLC	D/E	D	D
SMTC	D/E	D	D

3.4 V_{S30} and Site Class

To further analyse the site class details, and determine the relationship between V_S and site class, the average shear wave velocity to a depth of 30 m (V_{S30}) was defined for each SMS. This was calculated using equation 2 for the profile down to 30 m depth. The V_{S30} values for site class C, D, and E/E* are presented in a boxplot format in Figure 4.

Site class D locations have V_{S30} values between 192 and 452 m/s with a median value of 221 m/s. The interquartile range is between 211 and 270 m/s. Site class E/E* locations have V_{S30} values between 146 and 218 m/s with a median value of 187 m/s. The interquartile range is between 179 and 202 m/s, indicating that the 25th percentile V_{S30} for site class D is greater than the 75th percentile V_{S30} for site class E/E*. Overall there is a good delineation between the V_{S30} values for site class D and E/E*.

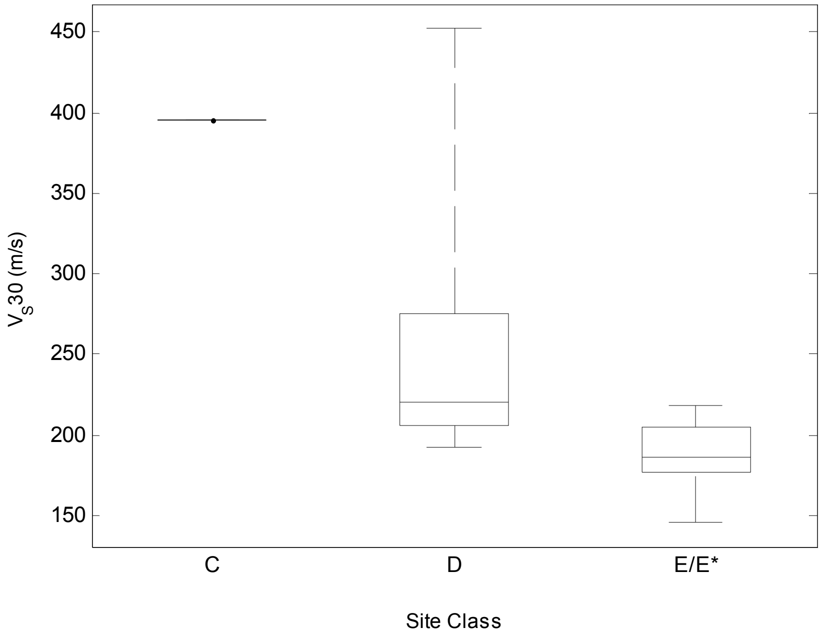

Figure 4 Box plot comparing V_{S30} values and site class for the preferred site class definitions

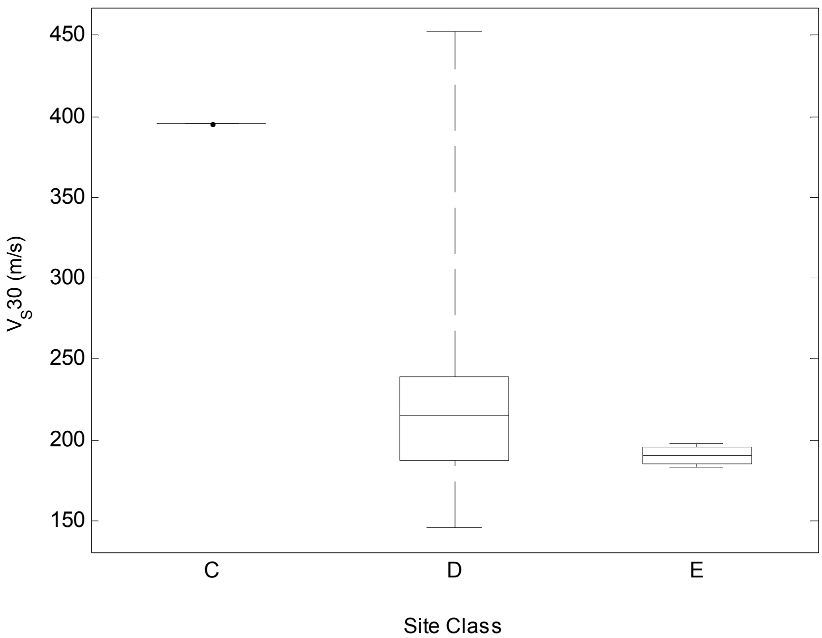

Figure 5 Box plot comparing V_{S30} values and site class for the strictly applied site class definitions

To identify the effect of the strict application of the site class definitions from NZS1170.5, without the application of the sliding site class E boundary, a boxplot of the V_{S30} values for the strictly applied site class C, D, and E is presented in Figure 5. This significantly affects the range of the V_{S30} values for site class D. Site class D locations have V_{S30} values between 146 and 452 m/s, extending to much lower values than the preferred site class definitions. However, the median value remains relatively constant, shifting from 210 to 215 m/s. Site class E locations have V_{S30} values between 184 and 198 m/s with a median value of 190 m/s. This median value falls within the interquartile range of the site class D values, with the entire site class E range inside the overall site class D range.

Assessment of the two site class definitions indicates the shortcomings of strictly applying the site class definitions, compared to the application of the sliding scale to the site class E boundary.

3.5 Liquefaction

A summary of the liquefaction triggering assessments, observed liquefaction surface manifestations and ground motions characteristics at each SMS is provided in Table 8. In general, the characteristics of the recorded ground motions at each site correlate well with the triggering analyses. However, at sites that likely liquefied at depth (as indicated by triggering analyses and/or inferred from the characteristics of the recorded surface acceleration time series), the presence of a non-liquefiable crust layer at many of the SMS locations prevented the manifestation of any surface effects.

Table 8 Summary of liquefaction triggering and the observed ground motion and surface manifestations

Code	Darfield Earthquake			Christchurch Earthquake		
	Triggering calculations	Surface manifestation	Ground motion characteristics	Triggering calculations	Surface manifestation	Ground motion characteristics
CACS	NA	N	N	NA	N	N
CBGS	N	N	N	Y	N	Y
CCCC	N	N	N	Y	Y	Y
CHHC	N	N	N	Y	Y	Y
CMHS	Y	N	N	Y	Y	Y
HPSC	N	Y	Y	Y	Y	Y
HVSC	N	N	N	N	N	N
KPOC	NA	N	N	NA	N	N
NBLC	N	N	NA	Y	N	NA
NNBS	N	N	N	Y	N	Y
PPHS	N	N	N	N	N	N
PRPC	N	N	N	N	Y	Y
REHS	Y	N	N	Y	N	Y
RHSC	NA	N	N	NA	N	N
SHLC	Y	N	N	Y	Y	Y
SMTC	NA	N	N	NA	N	N

4 Individual Christchurch Strong Motion Station Characteristics

This section summarises the geotechnical site investigation, NZS1170.5 site class, and liquefaction characteristics at each of the SMS locations. Summary figures of the geotechnical investigations at each SMS are presented in Appendix A, summaries of the liquefaction triggering calculations are presented in Appendix B, and a complete collation of the geotechnical investigation data at each SMS is presented in Appendix C.

4.1 Canterbury Aero Club (CACS)

The CACS SMS is housed in a single storey hanger with a shallow concrete pad foundation (approx. 30 x 50 m). Borehole and SPT data within 50 m of the SMS is summarised in Figure 6, with soil type from the borehole logs represented in the left hand plot. No CPT soundings were carried out as the profile was dominated by gravels from the surface. The borehole was terminated at a depth of 15.24 m as progressing the borehole became difficult due to the increasingly stiff nature of the gravel deposits. SPT N_{60} values were greater than 50 at all but one of the test depths.

Shear wave velocity data from surface wave measurements performed 30 m from the SMS is summarised in Figure 6. This profile indicates that the gravels at this location have V_s increasing from 282 m/s at the ground surface to 700 m/s at 14 m depth. This profile has significantly higher near surface V_s than the other sites on the flat areas of Christchurch presented herein.

4.1.1 Site Class

Bedrock was not encountered in any of the in-situ tests at this location. An H/V spectral peak at 6.33 seconds was measured from ambient noise recordings, likely corresponding to the natural period of the deposits above bedrock (See Appendix C). This puts the location well outside the site class C limits for fundamental site period.

SPT N_{60} values are consistently above 50 blows/0.3 m (blows/0.3 m is implied in the remainder of this report) throughout the soil profile, which is well in excess of the site class E limit of 6. The entire V_s profile is greater than the 150 m/s limit for site class E. Therefore, using the NZS1170.5 site class definitions, the CACS SMS is defined as site class D based on both SPT N_{60} and V_s.

4.1.2 Liquefaction Triggering

There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. As the profile was dominated by gravels with N_{60}>40, no liquefaction triggering calculations were carried out for this site. Acceleration records from the Darfield and Christchurch earthquakes had no indication of the occurrence of liquefaction in the underlying soils.

4.2 Canterbury Botanical Gardens (CBGS)

The CBGS SMS is housed in a one storey wooden building with a shallow concrete pad foundation (approx. 5 x 10 m). Borehole, SPT and CPT data within a few metres of the SMS is summarised in Figure 7, with the soil type from the borehole logs and I_c values from a CPT sounding represented in the left hand plots. Borehole logs indicate approximately 9 m of gravels at the surface with SPT N_{60} values of 30 and above. Beneath these surface gravels are interbedded layers of sands, sandy silts and silts down to 21 m. I_c values also indicate the variability of deposits within the 9-21 m depth range. Good correlation is shown between the SPT N_{60} values and the equivalent SPT N_{60} values from the CPT sounding in these layers. The Riccarton Gravels were encountered at a depth of 21 m, coinciding with a sharp increase in SPT N_{60} values to greater than 50.

Shear wave velocity data from surface wave measurements performed 20 m from the SMS are summarised in Figure 7. This profile indicates some soft surface deposits, underlain by 8 m of deposits with a V_s of 183 m/s. Below this there is a reduction in the V_s to 152 m/s in the softer interbedded sands, sandy silts and silts. At a depth of approximately 21 m, there is an increase in the V_s to 460 m/s, correlating to the depth of the Riccarton Gravels at this location.

4.2.1 Site Class

Using the depth to gravel and the V_s profile information, the estimated natural period of the deposits above the Riccarton Gravels was equal to 0.51 seconds. This shows good agreement with the 0.45 seconds H/V spectral peak reported by Wood et al. (2011). An H/V spectral peak at 0.69 seconds from ambient noise recordings summarised in Appendix C may also correspond to the period of these near surface deposits, however this does not agree well the previous two values. Bedrock was not encountered in any of the in-situ tests at this location, and the site period for the top 30 m of the V_s profile was estimated to be 0.61 seconds. Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. This puts the location outside the site class C limits for fundamental site period.

Approximately 4 m of soils have SPT N_{60}<6, much less than 10 m limiting thickness for site class E. The V_s measurements indicate that there is 11.3 m of soil with a V_s ≤152 m/s, which is close enough to the site class E limit of 150 m/s for a classification of site class E to be appropriate. Therefore, using the NZS1170.5 site class definitions, the CBGS SMS is defined as site class D based on SPT N_{60} and site class E based on V_s.

4.2.2 Liquefaction Triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake only a small number of very thin layers were shown to have a factor of safety slightly less than one throughout the soil profile. For the Christchurch earthquake multiple layers up to 40 cm in thickness were shown to liquefy throughout the soil profile, with the factors of safety of these layers equal to approximately 0.5. These potentially liquefiable layers sit below the approximately 9 m of surface gravels.

These calculations correlate well with the observations of no clear manifestation of liquefaction effects at the ground surface in the immediate vicinity of the SMS or evidence of liquefaction in the acceleration record following the Darfield earthquake. There was also no clear manifestation of liquefaction effects near the SMS following the Christchurch earthquake. However, the acceleration record from the Christchurch earthquake showed a clear indication of liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). A few hundred metres to the north of the SMS, significant volumes of ejecta were evident at the ground surface in North Hagley Park following the

Christchurch earthquake. This indicates that liquefaction likely occurred during the Christchurch earthquake. However, the thick gravel layer near the surface simply prevented surface manifestation of liquefaction near the SMS.

4.3 Christchurch Cathedral College (CCCC)

The CCCC SMS is housed in a two storey concrete walled building with a shallow concrete pad foundation (approx. 10 x 25 m). This is the footprint of a section of the overall structure, with additional sections of the structure connected to this, resulting in a complex structural arrangement. Data from a CPT sounding 45 m from the SMS is summarised in Figure 8Figure 8, with I_c represented in the left hand plot. The CPT met refusal at a depth of 25 m, likely coinciding with the depth of the Riccarton Gravels at this location. I_c values indicate sands and silty sands between 5 and 15 m, and interbedded layers of sands and silts between 15 and 20 m. From 20 to 25 m the I_c values suggest there is clayey silts and organic materials. Equivalent SPT N_{60} values from the CPT sounding increased from 6 to 50 between 5 and 15 m, and then vary between 6 and 40 through the interbedded sands and silts from 15 to 20 m, with lower values in the silt layers. The 20 to 25 m layer is much softer, with SPT N_{60} values between 4 and 7.

Data from investigations surrounding the SMS, up to a distance of 320 m, are summarised in Appendix C and compared to the CPT sounding in close proximity to the SMS. The geotechnical variability of the area surrounding the SMS was determined based on three CPT soundings between 160 and 320 m away from the SMS, and two boreholes/SPT logs 240 and 320 m away from the SMS. All investigations indicate a similar soil profiles and SPT N_{60} values in this area. Based on borehole data, the material in the 20 – 25 m range is likely sandy silts and organics silts. The Riccarton Gravels were encountered at depths of between 23 and 27 m at all these locations.

Shear wave velocity data from surface wave measurements performed 50 m from the SMS are summarised in Figure 8. This profile indicates soft surface deposits with a V_s less than 150 m/s down to a depth of 10 m, which is underlain by 10 m of soil with a V_s of 200 to 210 m/s. There is a reduction in the V_s to 150 m/s in the sandy silts/organic silts between 20 and 25 m. Below 25 m the V_s increases in the Riccarton Gravels to 450 m/s.

4.3.1 Site Class

Using the depth to gravel and the V_s profile information, the estimated natural period of the deposits above the Riccarton Gravels was equal to 0.63 seconds. This shows good agreement with the 0.71 second H/V spectral peak from ambient noise recordings (see Appendix C). An H/V spectral peak of 0.71 seconds was also reported by Wood et al. (2011). Bedrock was not encountered in any of the in-situ tests at this location. A second much longer H/V spectral peak was also measured at 2.37 seconds from ambient noise, likely corresponding to the natural period of the deposits above bedrock (see Appendix C). These values put the location outside the site class C limits for fundamental site period.

Approximately 6.5 m of soil have SPT N_{60}<6, less than the 10 m limiting thickness for site class E. The V_s measurements indicate that there is 10 m of the soil profile with V_s<150 m/s, matching the site class E cutoff of 10 m. Therefore, using the NZS1170.5 site class definitions, the CCCC SMS is defined as site class D based on SPT N_{60} and site class E based on V_s.

4.3.2 Liquefaction Triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake only a small number of thin layers were shown to have a factor of safety less than one throughout the soil profile. For the Christchurch earthquake thicker layers were predicted to liquefy throughout the soil profile, with lower factors of safety. The most substantial is a 1 m thick layer at a depth of 8 m, shown to be a clean sand-silty sand layer of moderate density. It should be noted that calculations below a depth of 20 m are outside the suggested depth range applicable for this method.

These calculations correlate well with the observations of surface manifestations following each event. There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following the Darfield earthquake. Minor volumes of ejecta were evident in the area surrounding the SMS following the Christchurch earthquake, with a few isolated sand boils approximately 50 m from the SMS location. It is likely that the depth and thickness of the layer described above minimised the severity of this surface manifestation.

The acceleration record from the Christchurch earthquake shows clear indication of liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake had no clear indication of the occurrence of liquefaction in the underlying soils.

4.4 Christchurch Hospital (CHHC)

The CHHC SMS is housed in the basement level of a large 2-storey reinforced concrete building with a shallow concrete pad foundation (approx. 25 x 55 m). Borehole and SPT data 55 m north of the SMS, and CPT soundings within 55 m from the SMS are summarised in Figure 9, with the soil type from the borehole logs and I_c values from the CPT soundings represented in the left hand plot. Borehole logs indicate layered deposits of sands and gravels to a depth of between 10 and 15 m. SPT N_{60} values are initially between 10 and 20 from the ground surface to 3 m depth, increasing to between 20 and 50 in the 3 -15 m depth range. A stiff sand layer is located beneath these interbedded layers, varying in thickness by between 4 and 8 m. A soft, 4 m thick layer of silts and organics, with SPT N_{60} values less than 15, sits between the sand layer and the stiff Riccarton Gravels below. I_c values from the CPT soundings correlate well with the soil types identified in the borehole logs, and both profiles meet refusal at the Riccarton Gravels, approximately 22 m deep. The equivalent SPT N_{60} values from the CPT soundings highlight the effect of the interbedding in the upper section of the profile.

Shear wave velocity data from surface wave measurements performed 95 m to the north of the SMS are summarised in Figure 9. This profile indicates that below soft surface deposits with a V_s of 130 m/s, the V_s remains constant at 185 m/s from 3.5 to 17.5 m through the sand and gravel layers. The V_s reduces to 145 m/s in the soft silt and organic layers and increases to 350 m/s in the Riccarton Gravels.

4.4.1 Site Class

Using the depth to gravel and the V_s profile information, the estimated natural period of the deposits above the Riccarton Gravels was equal to 0.52 seconds. This shows good agreement with the 0.53 seconds H/V spectral peak reported by Wood et al. (2011). An H/V spectral peak at 0.74 seconds data from ambient noise recordings summarised in Appendix C may also corresponds to the period of the deposits above the Riccarton Gravels, however this value is larger than the previous two estimates. Bedrock was not encountered in any of the in-situ tests at this location, and the site period for the top 34 m of the V_s profile was estimated to be 0.66 seconds. Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. This puts the location outside the site class C limits for fundamental site period.

Approximately 6 m of soil have SPT N_{60}<6, much less than 10 m limiting thickness for site class E. The V_s measurements indicate that there is 7.9 m of the soil profile with a V_s slightly less than 150 m/s, below the site class E cutoff of 10 m. As the V_s is not significantly less than the 150 m/s site class E limit over this 7.9 m depth, this location aligns to site class D. Therefore, using the NZS1170.5 site class definitions, the CHHC SMS is defined as site class D based on both SPT N_{60} and V_s.

4.4.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake only a small number of thin layers were shown to have a factor of safety less than one throughout the soil profile. For the Christchurch earthquake much thicker layers were predicted to liquefy throughout the soil profile, with much lower factors of safety. It should be noted that calculations below of a depth of 20 m are outside the suggested depth range applicable for this method.

These calculations correlate well with the observations of surface manifestations following each event. There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following the Darfield earthquake, and minor-moderate volumes of ejecta in the area immediately adjacent and surrounding the SMS following the Christchurch earthquake.

Acceleration records also correlated well with these calculations, with the acceleration record from the Christchurch earthquake showing a clear indication of liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake showed no indication of the occurrence of liquefaction in the underlying soils.

4.5 Cashmere High School (CMHS)

The CMHS SMS is housed in the basement of two storey timber building with shallow concrete pad foundation (approx. 25 x 40 m). Borehole and SPT data 45 m north of the SMS, and data from a CPT sounding 160 m from the SMS are summarised in Figure 10, with the soil type from the borehole logs and I_c values from the CPT sounding represented in the left hand plots. Borehole logs indicate approximately 7.5 m of gravels and sandy gravels at the surface overlying interbedded layers of sands, sandy silt and silt down to 13.8 m. The surface gravels generally have SPT N_{60} values greater than 33. SPT N_{60} values between 6 and 18 were recorded in the interbedded layers below, with the lowest blow count in a silty fine sand layer. Below this are gravel deposits that extend to the base of the borehole at 31.75 m depth, with SPT N_{60} values generally in excess of 50 throughout the gravel. Further east of the SMS, the I_c values from the CPT sounding show no indication of the surface gravel layers encountered in the borehole, with interbedded sands and silts replacing the gravel surface layer. These layers had equivalent SPT N_{60} values of 10 or less down to a depth of 10 m, with these values correlating well to the borehole SPT N_{60} values in the interbedded sands and silts below the gravels. The CPT sounding met refusal at a depth of 13.2 m, again correlating well to the lower gravels encountered in the borehole. The SMS is located in a region where surface gravels are present.

Shear wave velocity data from surface wave measurements performed 35 m to the east of the SMS are summarised in Figure 10. The V_s profile is located in the transition zone between the regions where surface gravels are and are not present. The V_s of sand and silt layers from the ground surface to the gravels gradually increase from 100 m/s to 170 m/s. At 14 m deep, the gravel has a V_s of 300 m/s, increasing to 400 m/s at 24 m depth.

Further north of the SMS, two shallower V_s profiles were measured within and outside the zone of near surface gravel. In the western location, a 2.5 m thick layer with a V_s of 180 m/s is present at the surface, while the location to the east has 7.6 m thick layer at the surface with a V_s of 100 m/s. It is likely that the higher V_s corresponds to a surface gravel layer in the western location. Clearly, there is significant lateral variability below the surface in this area down to a depth of approximately 14 m, below which there seems to be a consistent gravel layer.

4.5.1 Site Class

Bedrock was not encountered in by the CPT sounding and borehole at this location, and the site period for the top 45 m of the V_s profile was estimated to be 0.69 seconds. This shows good agreement with the 0.71 second H/V spectral peak from ambient noise recordings (see Appendix C), likely corresponding to the period of the deposits above the volcanic rock. An H/V spectral peak of 0.72 seconds was also reported by Wood et al. (2011). These values put this location outside the site class C limits.

Approximately 4 m of soil have SPT N_{60}<6, much less than 10 m limiting thickness for site class E. Just to the east of the SMS, where no surface gravels were encountered, there is approximately 9 m of soil with N_{60} values at or below 6, which would be assigned a site class E*. Given that a surface gravel layer is present at the SMS location, a site class D is appropriate as this reduces the overall thickness of the softer soil in the profile.

The V_s measurements indicate that there is approximately 4 m of the soil profile with a V_s<150 m/s, well above the site class E limiting thickness of 10 m. Down to a depth of 14 m, the entire profile has a V_s<170 m/s. However, this does not take into account the surface gravels that are present as the SMS location, which are likely to have a V_s of 180 m/s as indicated in the shallow V_s measurements to the north of the SMS. This gravel layer reduces the thickness of the soft deposits, meaning that site class D is appropriate. Therefore, using the NZS1170.5 site class definitions, the CMHS SMS is defined as site class D using both SPT N_{60} and V_s.

4.5.2 Liquefaction triggering

Given that the SPT and CPT equivalent N_{60} values from the CPT sounding 160 m to the east of the SMS showed a good correlation in the layer between the surface and underlying gravels, the CPT data in this range was assumed to be applicable to the SMS location and was used in liquefaction triggering calculations outlined in Appendix B. For both the Darfield and Christchurch earthquakes, these calculations indicated similar potentially liquefiable layer thicknesses and depths, and a similar factor of safety for each layer.

There was no clear manifestation of liquefaction at the ground surface across the entire school site following the Darfield earthquake, even though the triggering calculations indicate potential for significant liquefaction in layers several metres thick. Following the Christchurch earthquake there was no surface evidence of liquefaction directly adjacent to the SMS. However, there was a distinct boundary between severe surface manifestation and no manifestation evident in the school grounds directly to the east and south of the SMS. These surface manifestation characteristics seem to agree well with the triggering calculations. The lack of surface manifestation at the SMS was simply due to the presence of a surface gravel layer. The closest manifestations were approximately 30 m to the east of the SMS. To the north and east of the SMS, this boundary is characterised by increased severity of surface manifestation, and is likely a result of the passage of liquefied material from beneath the gravel surface layer towards the region with no surface constraining layer.

The acceleration record from the Darfield event did not show any clear indication of liquefaction of the underlying soils. The acceleration record from the 2011 Christchurch earthquake showed a clear indication of liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011).

4.6 Hulverstone Drive Pumping Station (HPSC)

The HPSC SMS is housed in a single storey concrete masonry building with shallow concrete pad foundation (approx. 4 x 8 m) and attached to a larger embedded concrete structure (approx. 7 x 7 m) that is part of the pumping station. Borehole and SPT data 90 m from the SMS and data from a CPT sounding 10 m from the SMS is summarised in Figure 11, with the soil type from the borehole logs and I_c values from the CPT sounding represented in the left hand plot. Borehole logs indicate that the soil profile consists of silty sand and a small layer of peat down to a depth of 3.25 m. Below this, there are clean sand deposits to a depth of 30 m where the borehole is terminated. Closer to the SMS location, the I_c values from the CPT sounding also indicate that the soil profile is dominated by sands and silty sands, with no clear indication of any peats at this location. The CPT sounding met refusal at approximately 36 m, likely coinciding with the depth of the Riccarton Gravels. There is some agreement between the SPT N_{60} values from SPT and CPT data, with the CPT data indicating a gradual increase in SPT N_{60} values with depth from 6 near the ground surface up to 60 just above the depth of refusal.

Shear wave velocity data from surface wave measurements performed 15 m to the west of the SMS are summarised in Figure 11. This profile indicates some very soft surface deposits, with a V_s less than 110 m/s down to a depth of 8 m. Below this the V_s increases to 240 m/s, and increases again to 400 m/s at 18.4 m depth.

4.6.1 Site Class

Bedrock or gravel was not encountered in any of the in-situ tests at this location, and the site period for the top 36 m of the V_s profile was estimated to be 0.62 seconds. An H/V spectral peak of 0.45 seconds was reported in Wood et al. (2011), slightly less than this calculated value. The H/V spectral ratio data from ambient noise recordings summarised in Appendix C did not have any clear peaks indicative of site period. Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. Therefore, this location is outside the site class C limits for fundamental site period.

Approximately 6 m of soil have SPT N_{60}<6, much less than 10 m limiting thickness for site class E. The V_s measurements indicate that approximately 8 m of the soil profile has a V_s<150 m/s, just below the site class E limiting thickness of 10 m. This does not strictly meet the site class E criteria, however given that this 8 m has a V_s less than 75% of the 150 m/s limit, a classification of site class E* was deemed appropriate. Therefore, using the NZS1170.5 site class definitions, the HPSC SMS is defined as site class D based on SPT N_{60} and site class E* based on V_s.

4.6.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake only a single thin layer was shown to have a factor of safety less than one throughout the soil profile. For the Christchurch earthquake similar characteristics were identified. It should be noted that calculations below of a depth of 20 m are outside the suggested depth range applicable for this method.

These calculations do not correlate well to the observations of surface manifestations following the Darfield and Christchurch earthquakes. There was clear manifestation of liquefaction effects at the ground surface in a large area surrounding the SMS following both earthquakes, with lateral spreading and large volumes of ejecta. The effects were more severe in the Christchurch earthquake. This may have been due to the presence of initial shear stresses in the soil profile given its proximity to the Avon River. This is not typically taken into account in level-ground analysis, and may have reduced the CRR values.

The characteristics of the acceleration records correlated well with the liquefaction triggering calculations. The acceleration record from the Christchurch earthquake indicating liquefaction of the underlying soils, with characteristic acceleration spikes in the record (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake showed some indication of the occurrence of liquefaction in the underlying soils.

4.7 Heathcote Valley Primary School (HVSC)

The HVSC SMS is located at 25 m RL, a much higher elevation than the other SMS presented here. The sensor and equipment at this site are housed in a steel clad timber framed shed with a shallow slab foundation (approx. 8 x 9 m), which is attached to a larger building (14 x 25 m) of similar construction also on a shallow foundation. In-situ test data from five CPT soundings within 60 m of the SMS are summarised in Figure 12. Three CPT soundings reached refusal at a depth of approximately 17 m, and two at a depth of approximately 20 m. I_c values indicate that the majority of the profile consists of a mix of silty sands, sandy silts, clayey silts and silty clays. The variability of the equivalent SPT N_{60} values from the CPT soundings in this figure is not unexpected given the nature of the deposition and the variable particle sizing of the colluvium.

Shear wave velocity data from surface wave measurements performed 30 m to the west of the SMS are summarised in Figure 12. This profile indicates that between 1.1 m and 18 m the V_s increases from 270 to 340 m/s, showing that the near surface loess deposits at this site are much stiffer than the near surface alluvial deposits at most of the other locations presented herein. At a depth of 18 m the V_s increases to 760 m/s, suggesting the existence of bedrock at this depth.

4.7.1 Site Class

Using the depth to refusal and the V_s profile information, the estimated natural period of the deposits above rock was equal to 0.24 seconds. This shows good agreement with the 0.27 second H/V spectral peak from ambient noise recordings (see Appendix C). An H/V spectral peak of 0.42 seconds was reported by Wood et al. (2011), higher than the previous two estimates but still less than 0.6 seconds. All these measurements put the location within the site class C limits for fundamental site period.

A representative lower bound SPT N_{60} value of 10 is appropriate for this site over a depth of 20 m, which is well within the site class C maximum depth limit of 40 m for this SPT N_{60} value. Additionally, there is less than 10 m of soils with N_{60}<6, the limiting criteria for site class E. Therefore, using the NZS1170.5 site class definitions, the HVSC SMS is defined as site class D based on both SPT N_{60} and V_s. It should be noted that this site is completely dominated by basin-edge effects (Bradley 2012), and as such it doesn’t behave at all like any of the standard site classes.

4.7.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and is outlined in Appendix B. Both the Darfield and Christchurch earthquakes had only a small number of thin layers that were shown to have a factor of safety less than one throughout the soil profile. The soil profile was dominated by material with higher I_c values, indicating that the soil profile is generally non-liquefiable.

This correlates well to the observations of surface manifestations following each event. There was no manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. Acceleration records from the Darfield and Christchurch earthquakes also had no indication of the occurrence of liquefaction in the underlying soils.

4.8 Kaiapoi North School (KPOC)

The KPOC SMS is housed in a single storey timber frame shed with iron cladding and a shallow concrete pad foundation (approx. 4 x 6 m). Borehole and SPT data within 50 m of the SMS is summarised in Figure 13, with the soil type from the borehole logs represented in the left hand plot. No CPT soundings were carried out as the profile was dominated by gravels. The borehole was terminated at a depth of 24.4 m as progressing the borehole became difficult due to the increasingly stiff nature of the gravel deposits. The soil profile is dominated by gravels from 3.5 m to the base of the borehole. Within this depth range are two thin soft sandy silt layers at depths of 12 and 18 m, and 1 m of thick poorly graded sand with trace gravel at 7.5 m depth. Apart from the silt layers, SPT N_{60} values are approximately 30 near the ground surface and increase to greater than 50 below 10 m.

Shear wave velocity data from surface wave measurements performed 40 m to the east of the SMS is summarised in Figure 13. This profile indicates soft surface deposits with a V_s less than 150 m/s down to depth of 6.4 m. Below this depth, the V_s gradually increases in the gravel deposits from 210 to 450 m/s.

4.8.1 Site Class

Using the 10.4 m depth to the stiff gravel and the V_s profile information, the estimated natural period of the deposits above the stiff gravel was equal to 0.26 seconds. This shows good agreement with the wide peak in the H/V spectral ratio data from ambient noise recordings between 0.22 and 0.31 seconds (see Appendix C). This shows good fairly good agreement with the H/V spectral peak of 0.36 seconds reported by Wood et al. (2011). Bedrock was not encountered in any of the in-situ tests at this location, and the site period for the top 50 m of the V_s profile was estimated to be 0.64 seconds. Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. This puts this location outside the site class C limits for fundamental site period.

Approximately 2 m of soil have a SPT N_{60}<6, much less than the 10 m limiting thickness for site class E. The V_s measurements indicate that 6 m of the soil profile has a V_s at or below 150 m/s, well below the site class E thickness limit of 10 m. Therefore, using the NZS1170.5 site class definitions, the KPOC SMS is defined as site class D based on both SPT N_{60} and V_s.

4.8.2 Liquefaction triggering

As the profile was dominated by gravels, no liquefaction triggering calculations were carried out for this site. SPT N_{60} values in the thin sandy layers were all above 30. Acceleration records from the Darfield and Christchurch earthquakes had no indication of the occurrence of liquefaction in the underlying soils. There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence.

4.9 New Brighton Library (NBLC)

The NBLC SMS is housed in the basement plant room of a two storey reinforced concrete building with slab foundation (Oval in plan approx. 20 x 65 m). Site investigation data is summarised in Figure 14, with a CPT sounding within 50 m of the SMS location. I_c values from the CPT sounding are summarised in the left hand plot in Figure 14. The I_c values indicate that the majority of the profile down to 45 m consists of sands and silty sands. The CPT sounding met refusal at this depth, likely corresponding to the depth of the Riccarton Gravels at this location. Equivalent SPT N_{60} values from CPT sounding are fairly constant at approximately 30 in the layer of sand between 3 and 21 m depth. Below this there is an increase in the SPT N_{60} values of the underlying sand layers, interbedded with finer grained silty sand and silt layers with much lower N_{60} values.

Shear wave velocity data from surface wave measurements performed 100 m to the north of the SMS are summarised in Figure 14. This profile indicates soft surface deposits with a V_s of between 120 and 165 m/s down to a depth of 12 m. Below this, the sand deposits stiffen, with the V_s increasing from 280 to 400 m/s.

4.9.1 Site Class

The H/V spectral ratio data from ambient noise recordings summarised in Appendix C did not have any clear peaks in the short period range. Bedrock was not encountered in any of the in-situ tests. An H/V spectral peak at 3.75 seconds, determined from ambient noise recordings, likely corresponds to the period of the deposits above bedrock (see Appendix C). This puts the location outside the site class C limits for fundamental site period.

SPT N_{60} values are consistently above 20 throughout the soil profile, which is well in excess of the site class E limit of 6. The V_s measurements indicate that approximately 3 m of the soil profile has a V_s<150 m/s, which is well above the site class E thickness limit of 10 m. This does not strictly meet the site class E criteria, however given that 12 m of the soil profile has a V_s of 165 m/s or less, a classification of site class E* was still deemed appropriate. Therefore, using the NZS1170.5 site class definitions, the NBLC SMS is defined as site class D based on SPT N_{60} and site class E* based on V_s.

4.9.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. No acceleration records were recorded at the site during either the Darfield or Christchurch earthquakes. However, to provide an indication of the possible response at this site, the geometric mean of the horizontal PGA from the nearby NNBS SMS was used as a representative PGA. For the Darfield earthquake only a small number of thin layers were shown to have a factor of safety less than one throughout the soil profile. However, for the Christchurch earthquake thicker layers were predicted to liquefy throughout the soil profile below a depth of 10 m, although these layers are likely to be too deep to result in any significant surface manifestation. It should be noted that calculations below of a depth of 20 m are outside the suggested depth range applicable for this method.

This correlates well to the observations of surface manifestations following each event. There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. The combination of the depth and thickness of the liquefiable layers means that it is not surprising there were no surface manifestations during the Christchurch earthquake. No acceleration records were recorded at this SMS for either the Darfield or Christchurch earthquakes.

4.10 North New Brighton School (NNBS)

The NNBS SMS is housed in a one storey concrete block shed with a shallow concrete pad foundation (approx. 5 x 7.5 m). Site investigation data is summarised in Figure 15, with two CPT soundings within 50 m of the SMS location. I_c values from the CPT soundings are summarised in the left hand plot. I_c values indicate that the profile consists of sands and silty sands down to a depth of 25 m. At this depth there is a transition to an approximately 1 m thick layer of clayey silt, before transitioning back to sands and silty sands. Equivalent SPT N_{60} values increase from 6 near the ground surface to 50 at the base of the CPT record, with a sharp reduction in the thin clayey silt layer.

Data from investigations within 160 m of the SMS are summarised in Appendix C and compared to the CPT soundings in close proximity to the SMS. Approximately 80 m from the SMS, a CPT was carried out to refusal at a depth of 40 m, where the cone likely encountered the Riccarton Gravels. This depth to the Riccarton Gravels has been deemed appropriate to classify the soil profile at the SMS. Data from a borehole 100 m to the west of the SMS show the transition from medium dense sand with trace silt to dense sand with minor silt at approximately 10 m depth, similar to what was indicated by the I_c values from the CPT soundings. SPT N_{60} values from the borehole and equivalent SPT N_{60} from the CPT sounding agree fairly well, indicating an increase in the penetration resistance of the profile at a depth between 10 and 12 m.

Shear wave velocity data from surface wave measurements performed 30 m from the SMS is summarised in Figure 15. The V_s profile indicates very soft surface deposits, with a V_s <131 m/s down to 6.3 m. Below this the V_s increases to 160 m/s over a depth of 5 m. At 11 m depth there is an increase in the V_s to 280 m/s which correlates well with the change in SPT N_{60} and stratigraphy shown in the other subsurface investigations. At 21 m depth the V_s increases to 350 m/s.

4.10.1 Site Class

The H/V spectral peak from ambient noise reported by Wood et al. (2011) was equal to 0.73 seconds. The H/V spectral ratio data from ambient noise recordings summarised in Appendix C did not have any clear peaks in the short period range. Bedrock was not encountered in any of the in-situ tests at this location. A longer period H/V spectral peak was measured at 4.87 seconds from ambient noise which likely corresponds to the natural period of the deposits above bedrock (see Appendix C). This puts the location outside the site class C limits for fundamental site period.

SPT N_{60} values were consistently above 20, which is well in excess of the site class E limit of 6. The V_s measurements indicate that approximately 6 m of the soil profile has a V_s<150 m/s, which is above the site class E limiting thickness of 10 m. This does not strictly meet the site class E criteria, however given that 11.2 m of the soil profile has a V_s of 160 m/s or less, a classification of site class E* was still deemed appropriate. Therefore, using the NZS1170.5 site class definitions, the NNBS SMS is defined as site class D based on SPT N_{60} and site class E* based on V_s.

4.10.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake only a single thin layers below 25 m was shown to have a factor of safety less than one. For the Christchurch earthquake thicker layers were predicted to liquefy throughout the soil profile below a depth of 7 m, with much lower factors of safety. It should be noted that calculations below of a depth of 20 m are outside the suggested depth range applicable for this method.

There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following the Darfield earthquake, correlating well with calculations. Following the Christchurch earthquake, there was no liquefaction manifestation at the ground surface in the direct vicinity of the SMS. However, 80 m to the north of the SMS there was a moderate volume of ejected sands on the school grounds. These regions with and without ejected material were separated by a slight elevation change (less than 0.5 m), with ejecta evident in the lower areas, but absent in the upper areas. The combination of the depth and thickness of the liquefiable layers means that it is not surprising there were no surface manifestations in this elevated area during the Christchurch earthquake.

Acceleration record characteristics showed good correlation with these calculations, with the acceleration record from the Christchurch earthquake indicating liquefaction of the underlying soils, with characteristic acceleration spikes prior to a sharp reduction in acceleration amplitude (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake had no clear indication of the occurrence of liquefaction in the underlying soils.

4.11 Papanui High School (PPHS)

The PPHS SMS is housed in a one storey high stud timber framed building with a shallow concrete pad foundation (approx. 10 x 20 m). Borehole and SPT data 5 m from the SMS and data from a CPT sounding 45 m from the SMS is summarised in Figure 16, with the soil type from the borehole logs and I_c values from the CPT sounding represented in the left hand plot. Borehole logs indicate that the soil profile consists of interbedded layers of soft sand, silty sand, silt and organics from the ground surface to a depth of approximately 10 m. Below this depth, there is approximately 7 m of gravels with SPT N_{60} values above 50, with gravels again dominating the profile below a depth of 19 m. Between these gravel layers is a 3 m thick silty sand layer with SPT N_{60} values between 0 and 16. The CPT sounding met refusal at approximately 10 m depth, correlating well to the depth of gravels at the borehole location. There is good agreement between the SPT N_{60} values from the borehole and equivalent SPT N_{60} from the CPT sounding, with values less than 6 over much of this depth range.

Shear wave velocity data from surface wave measurements performed 10 m to the west of the SMS is summarised in Figure 16. This profile indicates very soft surface deposits, with a V_s <120 m/s down to 9.5 m. Below this depth, the V_s increases sharply to 200 m/s in the 6.5 m thick gravel layers. The V_s reduces in the silty sand layer to 180 m/s, before increasing again to 450 m/s in the underlying gravels.

4.11.1 Site Class

Using the V_s profile information, the estimated natural period of the approximately 9 m of deposits above gravel was equal to 0.34 seconds. A second calculation using the V_s profile down to the top of the lower gravel layer at 19 m depth resulted in an estimated natural period of 0.53 seconds. This deeper profile estimated period shows good agreement with the 0.52 seconds H/V spectral peak from ambient noise recordings (see Appendix C). Bedrock was not encountered in any of the in-situ tests at this location. A second much longer H/V spectral peak was also measured at 5.91 seconds from ambient noise, likely corresponding to the natural period of the deposits above bedrock (see Appendix C). This puts the location outside the site class C limits for fundamental site period.

Approximately 8 m of soil has SPT N_{60}<6, less than the 10 m limiting thickness for site class E. This does not strictly meet the site class E criteria, however of this 8 m, 5 m has N_{60}<3. This is well below the site class E limit, suggesting that a classification of site class E* is appropriate. The V_s measurements indicate that there is 9.5 m of soil with a V_s<150 m/s, just below the site class E thickness limit of 10 m. This is near enough to the site class E limit for a classification of site class E to be appropriate. Therefore, using the NZS1170.5 site class definitions, the PPHS SMS is defined as site class E* based on SPT N_{60} and site class E based on V_s.

4.11.2 Liquefaction triggering

Given that the SPT and CPT equivalent N_{60} values showed a good correlation in the surface layer, the CPT data in this range was assumed to be applicable to the SMS location and was used in liquefaction triggering calculations outlined in Appendix B. For the Darfield earthquake only a few thin layers were shown to have a factor of safety less than one. For the Christchurch earthquake, a smaller number of layers were identified, with factors of safety closer to one.

This correlates well to the observations of surface manifestations following each event. There was no manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. Acceleration records from the Darfield and Christchurch earthquakes also had no indication of the occurrence of liquefaction in the underlying soils.

4.12 Pages Road Pumping Station (PRPC)

The PRPC SMS is housed in a one storey concrete masonry shed with a shallow concrete pad foundation (approx. 4 x 9 m). In-situ test data from four CPT soundings within 140 m of the SMS are summarised in Figure 17, with I_c represented in the left hand plot. Two CPT soundings reached refusal at depths of between 27 and 28 m, likely corresponding to the depth of the Riccarton Gravels at this location. I_c values indicate that the profile is dominated by sands and silty sands between depths of 3 and 20 m. Below this level the profile transitions to silts and clayey silt material for approximately 2 m in the CPT sounding closest to the SMS, then back into a sandy layer. There is another transition below this layer to silts and clayey silts down to the top of the underlying gravels. SPT N_{60} values increase from 6 near the ground surface to approximately 30 at a depth of 5 m, then there is a fairly linear increase up to 50 at 20 m depth. There is a sharp drop in the SPT N_{60} values in the underlying silt and clayey silt layers to between 6 and 20.

Shear wave velocity data from surface wave measurements performed 70 m to the north of the SMS is summarised in Figure 17. This profile indicates soft surface deposits with a V_s of 160 m/s between 2 and 10 m, increasing to 190 m/s over the next 10 m. Below this there is a reduction in the V_s to 140 m/s in the silty layers beneath. At 27 m, the V_s increases to 300 m/s in the Riccarton Gravels.

4.12.1 Site Class

Bedrock was not encountered in any of the in-situ tests at this location. Using the depth to gravel and the V_s profile information, the estimated natural period of the deposits above the Riccarton Gravels was equal to 0.66 seconds. This shows good agreement with the 0.61 second H/V spectral peak from ambient noise recordings (see Appendix C). This also agrees fairly well with the 0.83 second H/V spectral peak reported by Wood et al. (2011). Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. This puts the location outside the site class C limits for fundamental site period.

SPT N_{60} values are consistently above 20, which is well in excess of the site class E limit of 6. The V_s measurements indicate approximately 7.5 m of material has a V_s<150 m/s, which is less than the site class E limit of 10 m. This does not strictly meet the site class E criteria, however as there is approximately 15 m of soil with a V_s<160 m/s, a classification of site class E* was deemed appropriate. Therefore, using the NZS1170.5 site class definitions, the PRPC SMS has been defined as site class D based on SPT N_{60}, and site class E* based on V_s.

4.12.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake only a small number of thin layers below a depth of 20 m were shown to have a factor of safety less than one. Similar layers were shown to have a factor of safety less than one in the Christchurch earthquake, however in both cases it is unlikely that surface manifestations would result from a layer liquefying at this depth. It should be noted that calculations below of a depth of 20 m are outside the suggested depth range applicable for this method.

There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following the Darfield earthquake. A small volume of ejecta was evident in the area immediately adjacent and surrounding the SMS following the Christchurch earthquake.

The acceleration record from the Christchurch earthquake indicated liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake had no indication of the occurrence of liquefaction in the underlying soils.

4.13 Christchurch Resthaven (REHS)

The REHS SMS is housed in a single storey timber frame shed with a shallow concrete pad foundation (approx. 2 x 4 m). Site investigation data is summarised in Figure 18, with two CPT soundings within 15 m of the SMS location. I_c values from the CPT soundings are summarised in the left hand plot. One CPT sounding met refusal at a depth of 20 m, likely coinciding with the depth of the Riccarton Gravels at this location. I_c values suggest the upper 10 m consists of a mix of sands, silts, clayey silts and organic material. Equivalent SPT N_{60} values throughout the majority of these surface layers are at or below 6. A gravel layer was encountered at approximately 10 m depth, hence the gap in the CPT record from this depth down to 14 m. Between 14 and 20 m I_c values suggest sands and silty sands, with equivalent SPT N_{60} values of 40 and above.

Data from investigations surrounding the SMS up to a distance of 150 m are summarised in Appendix C and compared to the CPT soundings in close proximity to the SMS. The geotechnical variability of the area surrounding the SMS was determined based on five CPT soundings, located between 65 and 150 m from the SMS, and two boreholes/SPT data, located between 110 and 130 m from the SMS. All investigations indicate a similar soil profiles and SPT N_{60} values in this area. Based on borehole data, the soils down to a depth of 10 m are a mix of sands, silts and peats, correlating well with that suggested by the I_c values.

Shear wave velocity data from surface wave measurements performed adjacent to the SMS is summarised in Figure 18. This profile indicates very soft surface deposits, with a V_s at or below 95 m/s from the surface down to 9 m depth. The V_s increases to 170 m/s in the underlying gravels to a depth of 20 m, increasing again to 300 m/s below 20 m.

4.13.1 Site Class

Bedrock was not encountered in any of the in-situ tests at this location. Using the depth to gravel and the V_s profile, the estimated natural period of the deposits above the Riccarton Gravels was equal to 0.68 seconds. This also shows good agreement with the 0.65 second H/V spectral peak reported by Wood et al. (2011). This shows fairly good agreement with the 0.57 second H/V spectral peak from ambient noise recordings (see Appendix C). Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. This puts the location outside the site class C limits for fundamental site period.

Approximately 8 m of soils had SPT N_{60}<6, which is less than 10 m limiting thickness for site class E. This does not strictly meet the site class E criteria, however of this 8 m, 5 m have N_{60}<3. This is well below the limit for site class E, suggesting that a classification of site class E* is appropriate. The V_s measurements indicate that there is 8.8 m of soil with a V_s at or below 95 m/s, well below the 150 m/s limit and just less than the site class E thickness limit of 10 m. This does not strictly meet the site class E criteria, but suggests that a site class E* may be appropriate. Therefore, using the NZS1170.5 site class definitions, the REHS SMS has been defined as site class E* based on both SPT N_{60} and V_s.

4.13.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For the Darfield earthquake a small number of thin layers were shown to have a factor of safety less than one near the surface. For the Christhchurch earthquake the factor of safety in these same layers reduced, and the thickness of the potentially liquefiable layers increased to over 1 m.

There was no manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. This may be due to the presence of a thin gravel layer at the ground surface at this location.

The acceleration record from the Christchurch earthquake indicated liquefaction of the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake had no indication of the occurrence of liquefaction in the underlying soils.

4.14 Riccarton High School (RHSC)

The RHSC SMS is housed in a half embedded one storey concrete masonry boiler room with a shallow concrete pad foundation (approx. 3.5 x 3. m). This structure is attached to other larger adjacent structures. Borehole and SPT data, within 20 m of the SMS is summarised in Figure 19, with the soil type from the borehole logs represented in the left hand plot. No CPT soundings were carried out as the profile was dominated by gravels. Borehole logs indicate approximately 6.5 m of sands, silts and some organics at the surface overlying gravels. SPT N_{60} values in these surface layers were between 6 and 20. Apart from a handful of depths, SPT N_{60} values in the gravels were greater than 50. These lower SPT N_{60} values were likely a result of cobbles in the two deeper SPT test locations. The borehole was terminated at a depth of 27.38 m as progressing the borehole became difficult due to the increasingly stiff nature of the gravel deposits.

Shear wave velocity data from surface wave measurements performed 35 m to the west of the SMS is summarised in Figure 19. This profile indicates surface deposits with a V_s of 170m/s down to the top of the gravels at 6.5 m depth. In the gravel layers the V_s increases from 270 m/s to 430 m/s at a depth of 15.9 m.

4.14.1 Site Class

A H/V spectral peak of 0.35 seconds was reported by Wood et al. (2011). The H/V spectral ratio data from ambient noise recordings summarised in Appendix C did not have any clear peaks in the short period range. Bedrock was not encountered in any of the in-situ tests at this location. A much longer period H/V spectral peak at 5.2 seconds was measured from ambient noise recordings, likely corresponds to the natural period of the deposits above bedrock (see Appendix C). This puts the location outside the site class C limits for fundamental site period.

Approximately 5 m of soil have SPT N_{60}<6, which is much less than 10 m limiting thickness for site class E. Apart from the top 0.5 m, the entire V_s profile is above the site class E limit of 150 m/s. Therefore, using the NZS1170.5 site class definitions, the RHSC SMS has been defined as site class D based on both SPT N_{60} and V_s.

4.14.2 Liquefaction triggering

As the profile was dominated by gravels and the water table was below the surface deposits, no liquefaction triggering calculations were carried out for this site. There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. Acceleration records from the Darfield and Christchurch earthquakes showed no indication of the occurrence of liquefaction in the underlying soils. If the water table was closer to the ground surface the surface deposits may have liquefied as they had SPT N_{60} values less than 10.

4.15 Shirley Library (SHLC)

The SHLC SMS is housed in one storey timber framed building with a shallow concrete pad foundation (approx. 20 x 55 m). Site investigation data is summarised in Figure 20, with a CPT sounding within 55 m of the SMS location. I_c values from the CPT sounding are summarised in the left hand plot. The CPT sounding met refusal at a depth of 27.5 m, likely coinciding with the depth of the Riccarton Gravels. I_c values suggest that the profile is dominated by sands and silty sands from the surface down to 25 m. Equivalent SPT N_{60} values vary between 20 and 50 in this range. A thin gravel layer approximately 1 m thick is indicated at a depth of 4.5 m with higher SPT N_{60} values. Between 25 and 27.5 m, the soil transitions to a clayey silt, with SPT N_{60} values of between 5 and 10.

Shear wave velocity data from surface wave measurements performed 50 m to the north of the SMS is summarised in Figure 20. This profile indicates soft surface deposits with a V_s of 121 m/s down to 4 m depth. Below this depth, there is a gradual increase in the V_s from 180 to 220 m/s down to the top of the gravels at 27 m depth.

4.15.1 Site Class

Using the depth to gravel and the V_s profile information, the estimated natural period of the deposits above the Riccarton Gravels was equal to 0.57 seconds. This shows good agreement with the 0.61 second H/V spectral peak from ambient noise recordings (see Appendix C). This also shows good agreement with the 0.54 second H/V spectral peak reported by Wood et al. (2011). Bedrock was not encountered in any of the in-situ tests at this location, and the site period of the top 35 m of the V_s profile was estimated to be 0.64 seconds. Note that a much longer fundamental site period is expected for the entire soil profile down to bedrock. This puts the location outside the site class C limits for fundamental site period.

SPT N_{60} values are consistently above 20, which is well above the site class E limit of 6. The V_s measurements indicate approximately 3.5 m of material has a V_s<150 m/s, which is less than the site class E limiting thickness of 10 m. Therefore, using the NZS1170.5 site class definitions, the SHLC SMS has been defined as site class D based on both SPT N_{60} and V_s.

4.15.2 Liquefaction triggering

CPT data was used in liquefaction triggering calculations at this location and are outlined in Appendix B. For both the Darfield and Christchurch earthquakes only a small number of thin layers at depths greater than 15 m were shown to have a factor of safety less than one. It should be noted that calculations below of a depth of 20 m are outside the suggested depth range applicable for this method.

There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following the Darfield earthquake. Moderate volumes of ejecta were evident in the area immediately adjacent and surrounding the SMS following the Christchurch earthquake.

The acceleration record from the Christchurch earthquake indicated that liquefaction had occurred in the underlying soils, with characteristic acceleration spikes and reduced high frequency content in the latter part of the record (Bradley & Cubrinovski 2011). The acceleration record from the Darfield earthquake had no indication of the occurrence of liquefaction in the underlying soils.

4.16 Styx Mill Transfer Station (SMTC)

The SMTC SMS is housed in one storey concrete masonry building/garage with a shallow concrete pad foundation (approx. 12 x 7 m). Borehole and SPT data within 30 m of the SMS is summarised in Figure 21, with the soil type from the borehole logs represented in the left hand plot. No CPT testing was carried out as the profile was dominated by gravels. Borehole logs indicate that the profile is dominated by gravels from 2 to 11 m, interspersed with thin layers of organic sand and peat. SPT N_{60} values are 40 and above in this depth range. Between 11 and 18 m there are interbedded layers of stiff sands and soft silts, with SPT N_{60} values of zero in the silt layers, and 50 in the sand layers. Below this depth, the profile transitions back to gravels, with SPT N_{60} values of 50 and above. The borehole was terminated at a depth of 27.38 m as progressing the borehole became difficult due to the increasingly stiff nature of the gravel deposits.

Shear wave velocity data from surface wave measurements performed 40 m to the north of the SMS is summarised in Figure 21. This profile indicates shows a thin layer of surface deposits underlain the 10 m of gravels with a V_s of 230 m/s. There is then a sharp drop in the V_s to 140 m/s in the soft silty layers to a depth of 18 m. The V_s then increases again in the gravel layers at 18 m depth to 300 m/s.

4.16.1 Site Class

Using the depth to gravels and the V_s profile information, the estimated natural period of the deposits above the gravels at 18 depth was equal to 0.4 seconds. An H/V spectral peak at 0.54 seconds estimated using ambient noise recordings shows fairly good agreement with this value (see Appendix C). Bedrock was not encountered in any of the in-situ tests at this location. A second much longer H/V spectral peak at 6.25 seconds was also measured from ambient noise, likely corresponding to the natural period of the deposits above bedrock (see Appendix C). This puts the location outside the site class C limits for fundamental site period.

Approximately 5 m of soils have SPT N_{60}<6, which is much less than the 10 m limiting thickness for site class E. The V_s measurements indicate that 6 m of soil have a V_s<150 m/s, which is also less than the site class E thickness limit of 10 m. Therefore, using the NZS1170.5 site class definitions, the SMTC SMS has been defined as site class D based on both SPT N_{60} and V_s.

4.16.2 Liquefaction triggering

As the profile was dominated by gravels, no liquefaction triggering calculations were carried out for this site. SPT N_{60} values in the few sandy layers were all above 35. There was no clear manifestation of liquefaction effects at the ground surface in the immediate area surrounding the SMS following any of the major earthquakes in the Canterbury earthquake sequence. Acceleration records from the Darfield and Christchurch earthquakes showed no indication of the occurrence of liquefaction in the underlying soils.

5 Conclusions

This report has presented updated soil profile classifications of a selection of strong motion stations (SMSs) in the vicinity of Christchurch based on recently completed geotechnical site investigations. A complete collation of all the site investigation data used in the report are provided in the appendices.

Both SPT N_{60} and V_s based site classes did not always agree with the original site classifications, emphasising the importance of having detailed site-specific information at SMS locations in order to properly classify them. Site class E boundaries were treated as a sliding scale rather than as a discrete boundary to account for locations with similar site effects potential, an approach which was shown to result in a better delineation between the site classes. SPT N_{60} values often indicated a stiffer site class than the V_s data at softer soil sites, highlighting the disparity between the two site investigation techniques. Additional studies are required to harmonize site classification based on SPT N_{60} and V_s.

Liquefaction triggering assessments were carried out for the Darfield and Christchurch earthquakes. These assessments were compared against the observed liquefaction surface manifestations and the characteristics of ground motions recorded at each SMS. In general these calculations showed a good correlation to the characteristics of the recorded ground motions at each site. However, at sites that likely liquefied at depth, the presence of a non-liquefiable crust layer prevented the manifestation of any surface effects.

6 Acknowledgements

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We acknowledge the Canterbury Geotechnical Database for some of the site investigation data used in this study. EQC, CERA, their data suppliers and their engineers, Tonkin & Taylor, have no liability to any user of this data or for the consequences of any person relying on them in any way. We acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and LINZ, for providing some of the data used in this study. We also thank the land owners at all strong motion stations for their cooperation during this study, and the support of McMillans Drilling.

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Appendix A SMS Investigation Summaries

A summary of the site investigation data at each SMS in the form of soil type behaviour index (I_C), borehole logs, SPT blow counts ($SPT\ N_{60}$), and shear wave velocity (V_S) is presented in this Appendix. The data for each SMS is dependent on the site investigation methods used at each location. On each SPT blow count and V_S plot, the borderline between site class D and E is indicated by a dashed line, and the range ±10% from this borderline is shown by the shaded region.

A.1 Canterbury Aero Club

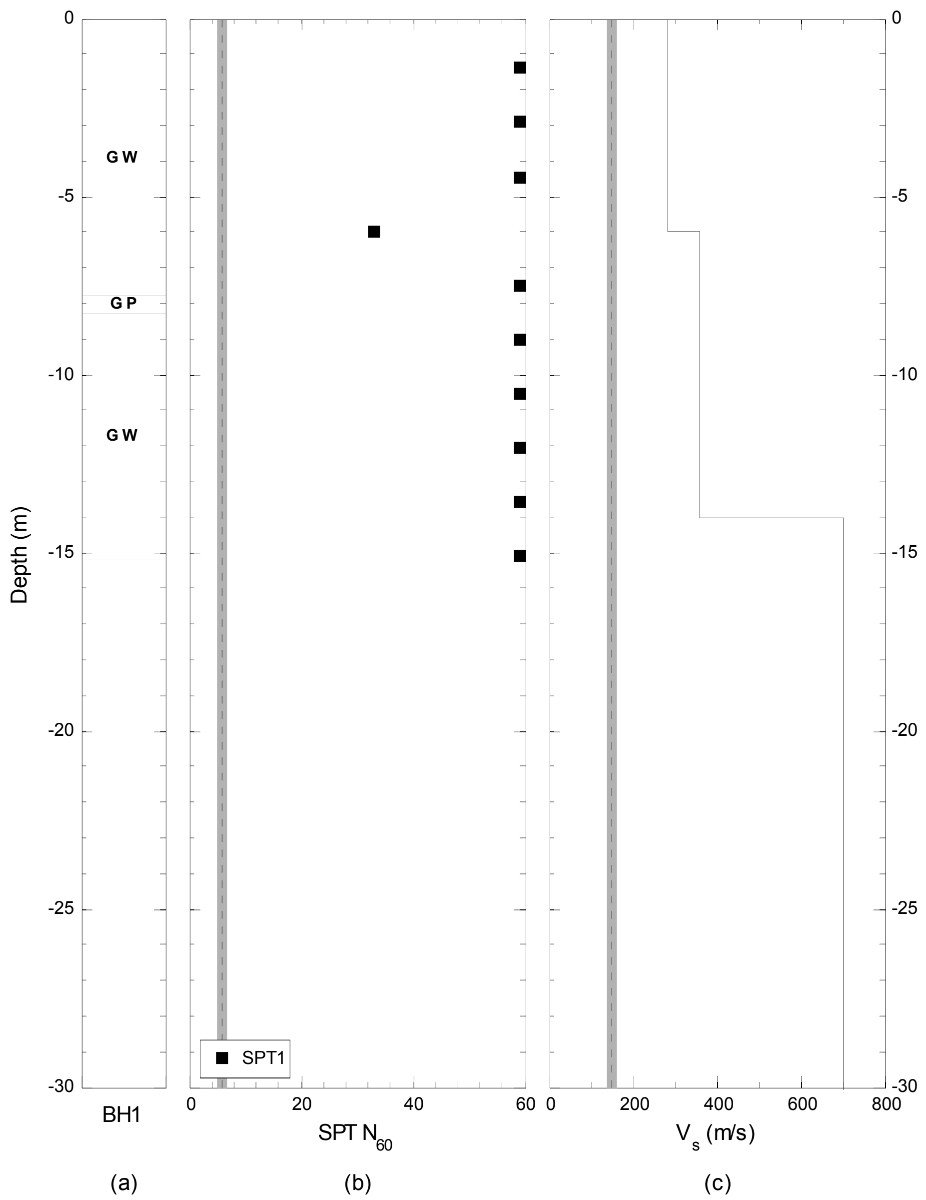


Figure 6 CACS geotechnical site investigation summary (a) borehole BH1 log, (b) SPT blow counts, (c) shear wave velocity

A.2 Christchurch Botanical Gardens (CBGS)

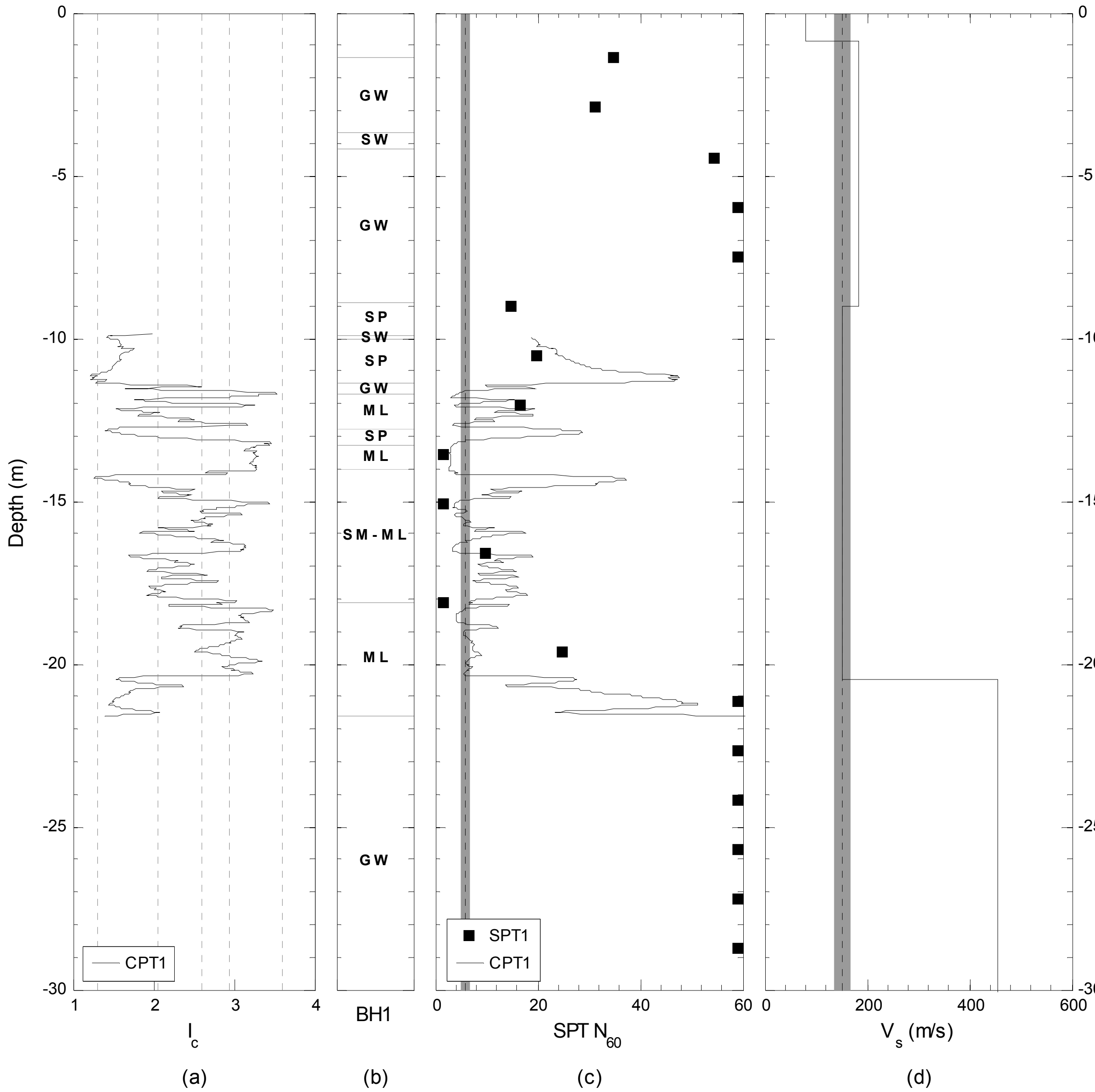


Figure 7 CBGS geotechnical site investigation summary (a) soil behaviour type index, (b) borehole BH1 log, (c) SPT blow counts, (d) shear wave velocity

A.3 Christchurch Cathedral College (CCCC)

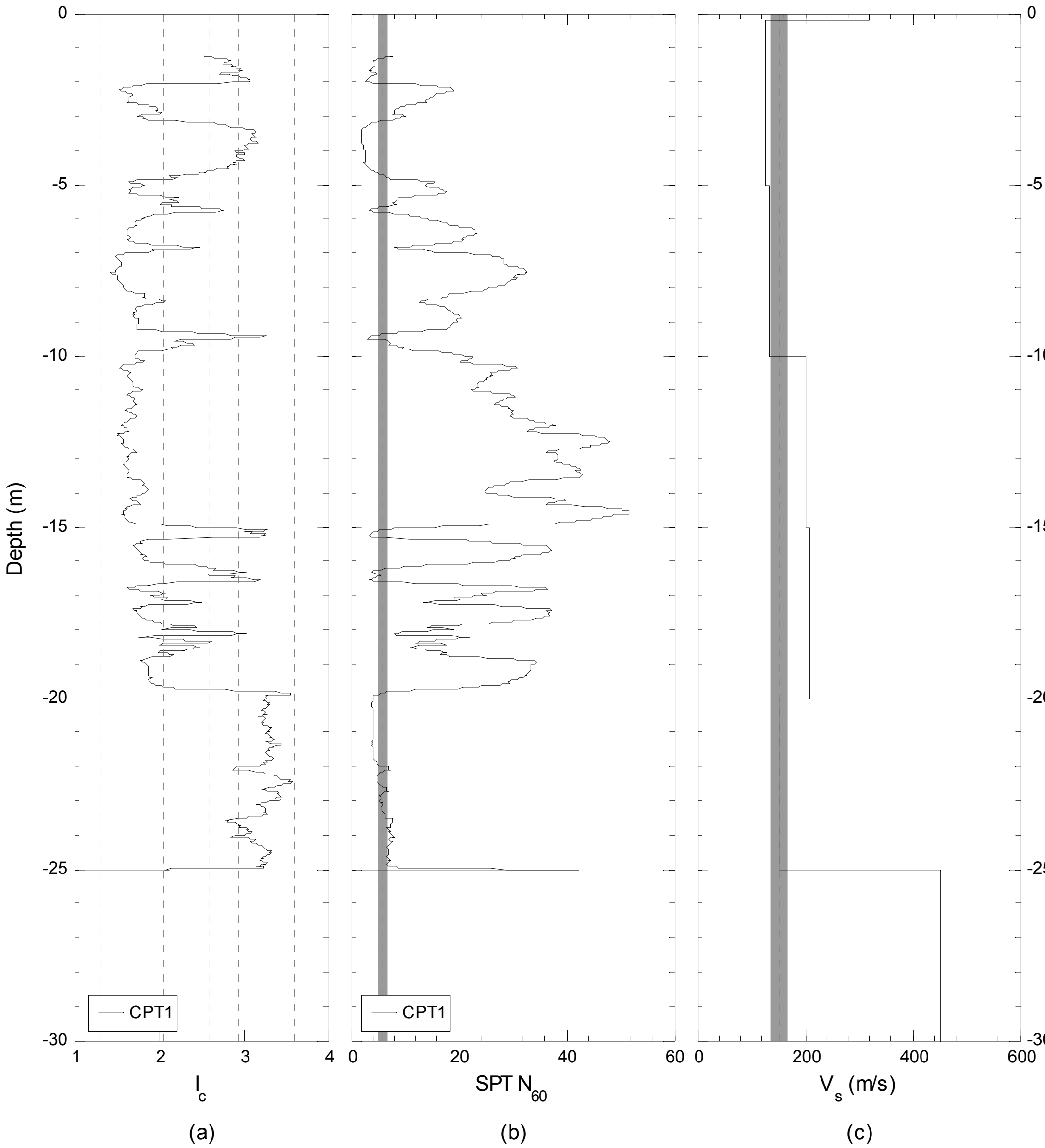


Figure 8 CCCC geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.4 Christchurch Hospital (CHHC)

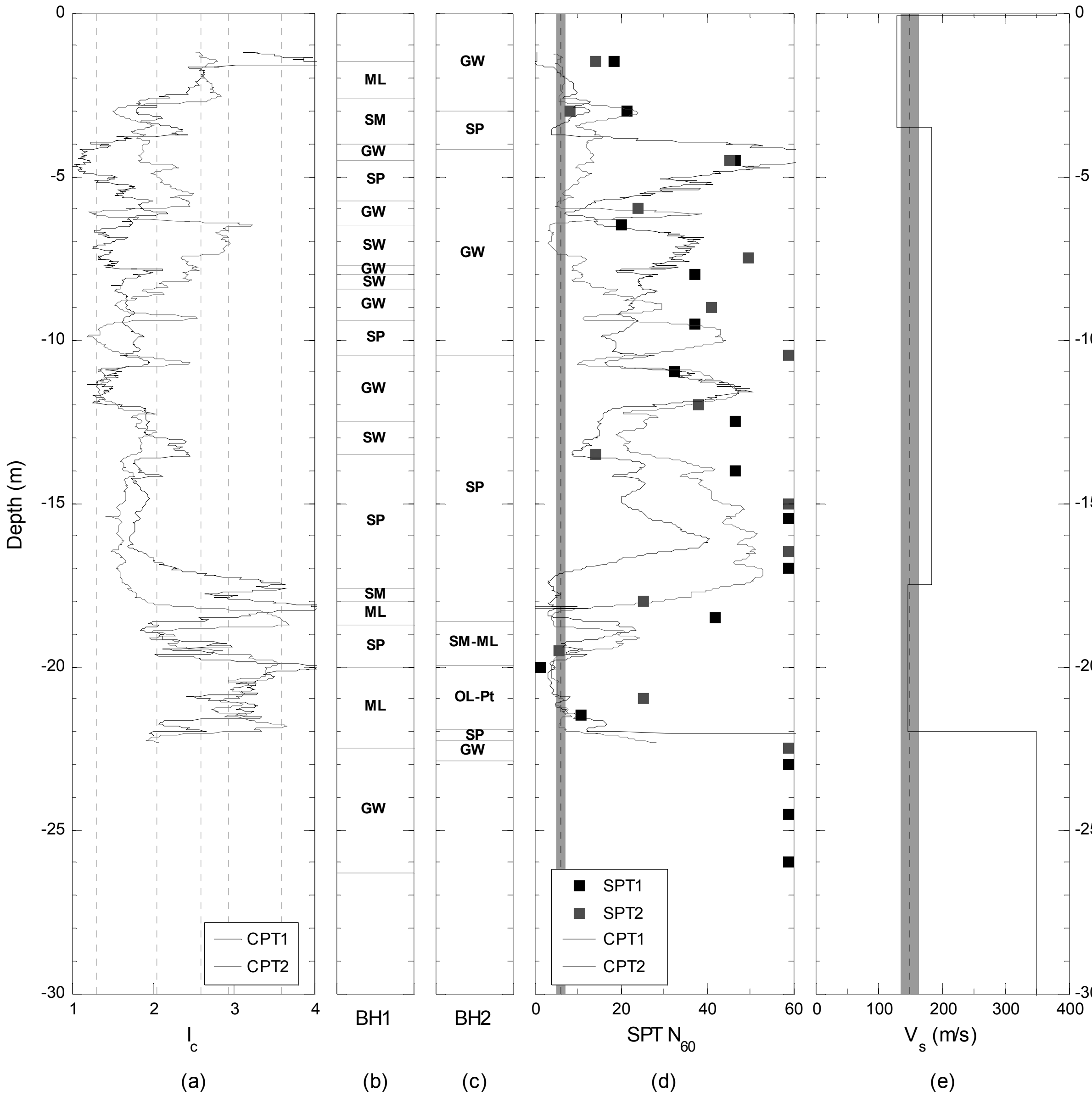


Figure 9 CHHC geotechnical site investigation summary (a) soil behaviour type index, (b) borehole BH1 log, (c) borehole BH2 log, (d) SPT blow counts, (e) shear wave velocity

A.5 Cashmere High School (CMHS)

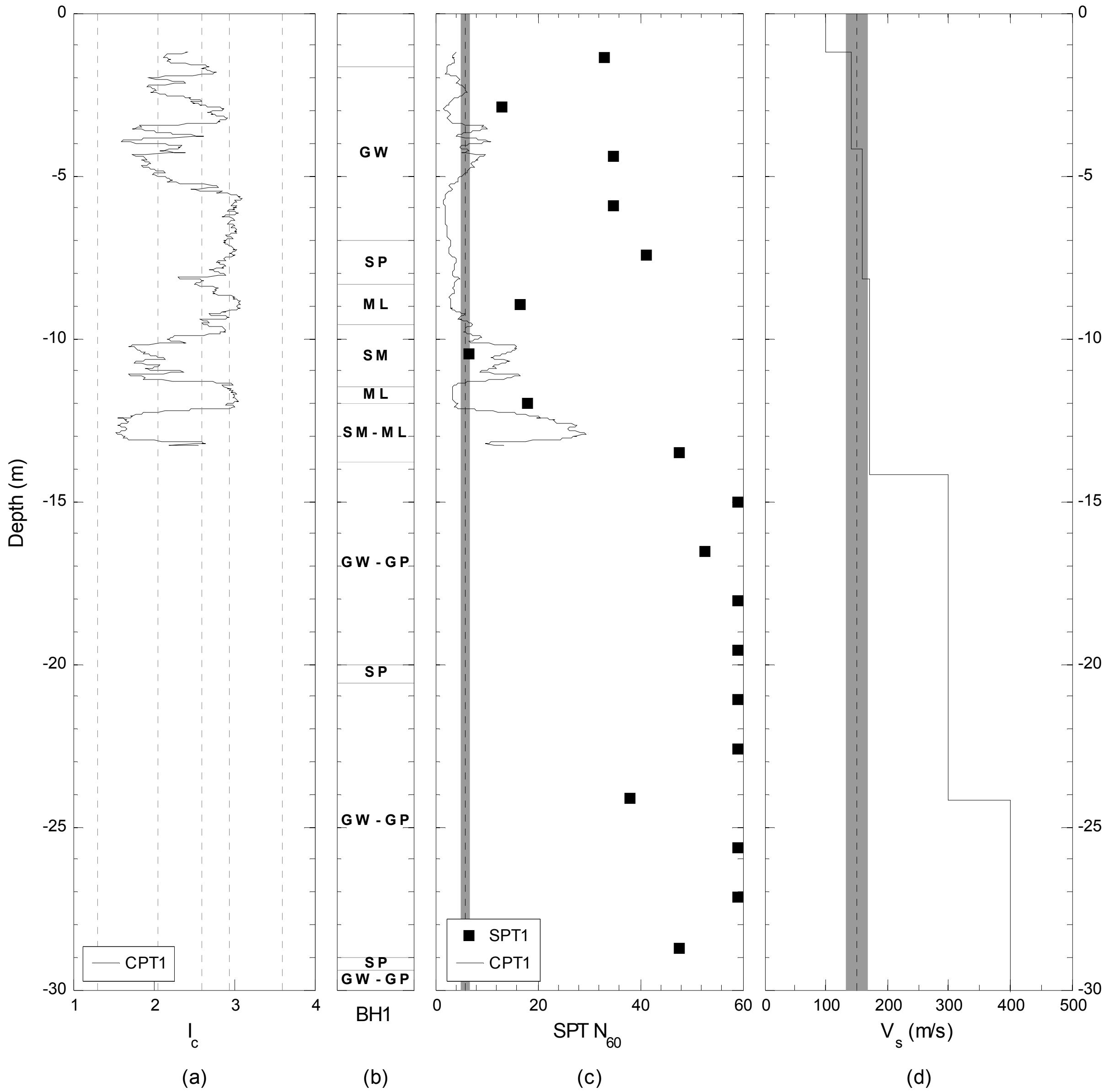


Figure 10 CMHS geotechnical site investigation summary (a) soil behaviour type index, (b) borehole BH1 log, (c) SPT blow counts, (d) shear wave velocity

A.6 Hulverstone Drive Pumping Station (HPSC)

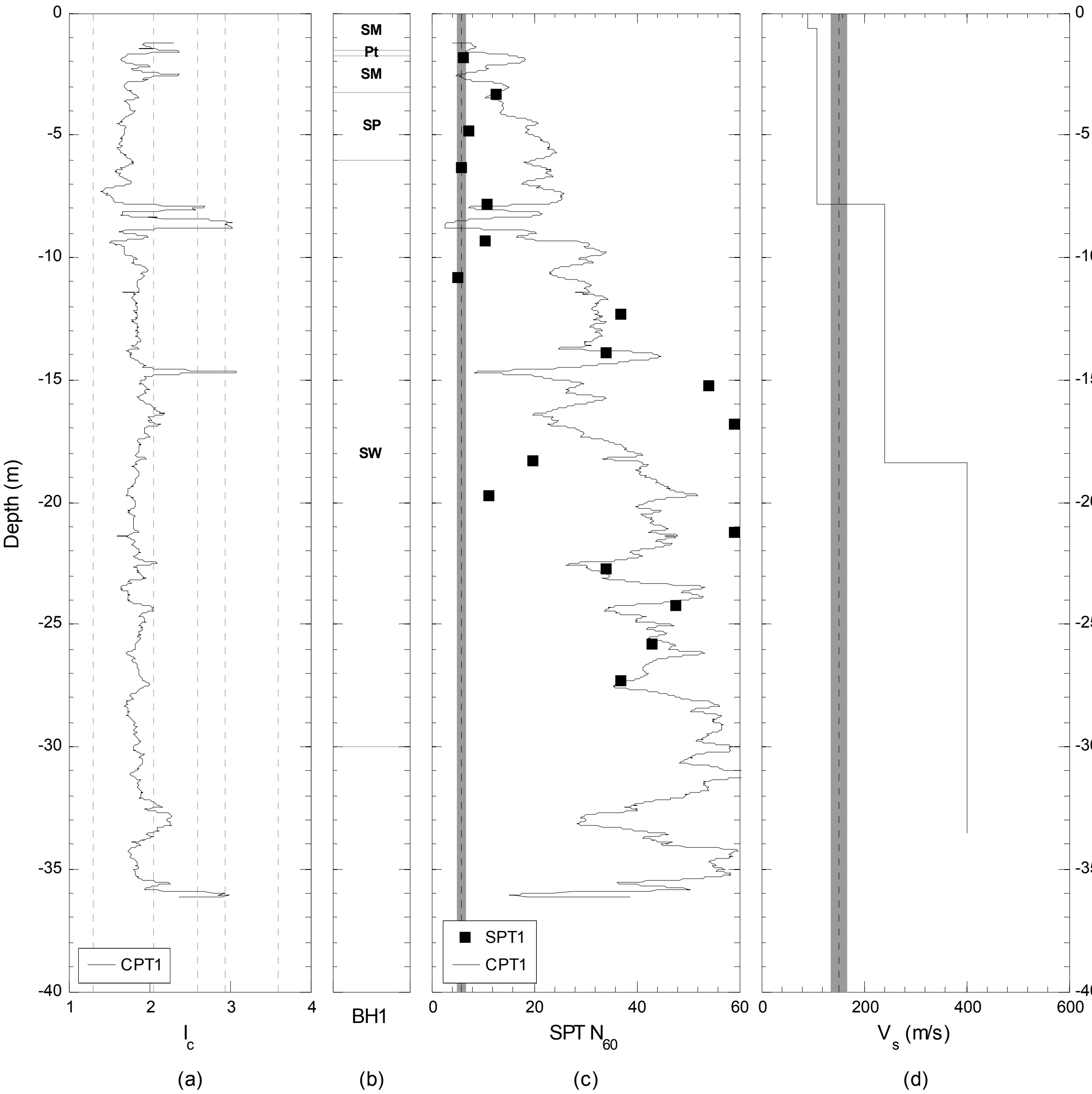


Figure 11 HPSC geotechnical site investigation summary (a) soil behaviour type index, (b) borehole BH1 log, (c) SPT blow counts, (d) shear wave velocity

A.7 Heathcote Valley Primary School (HVSC)

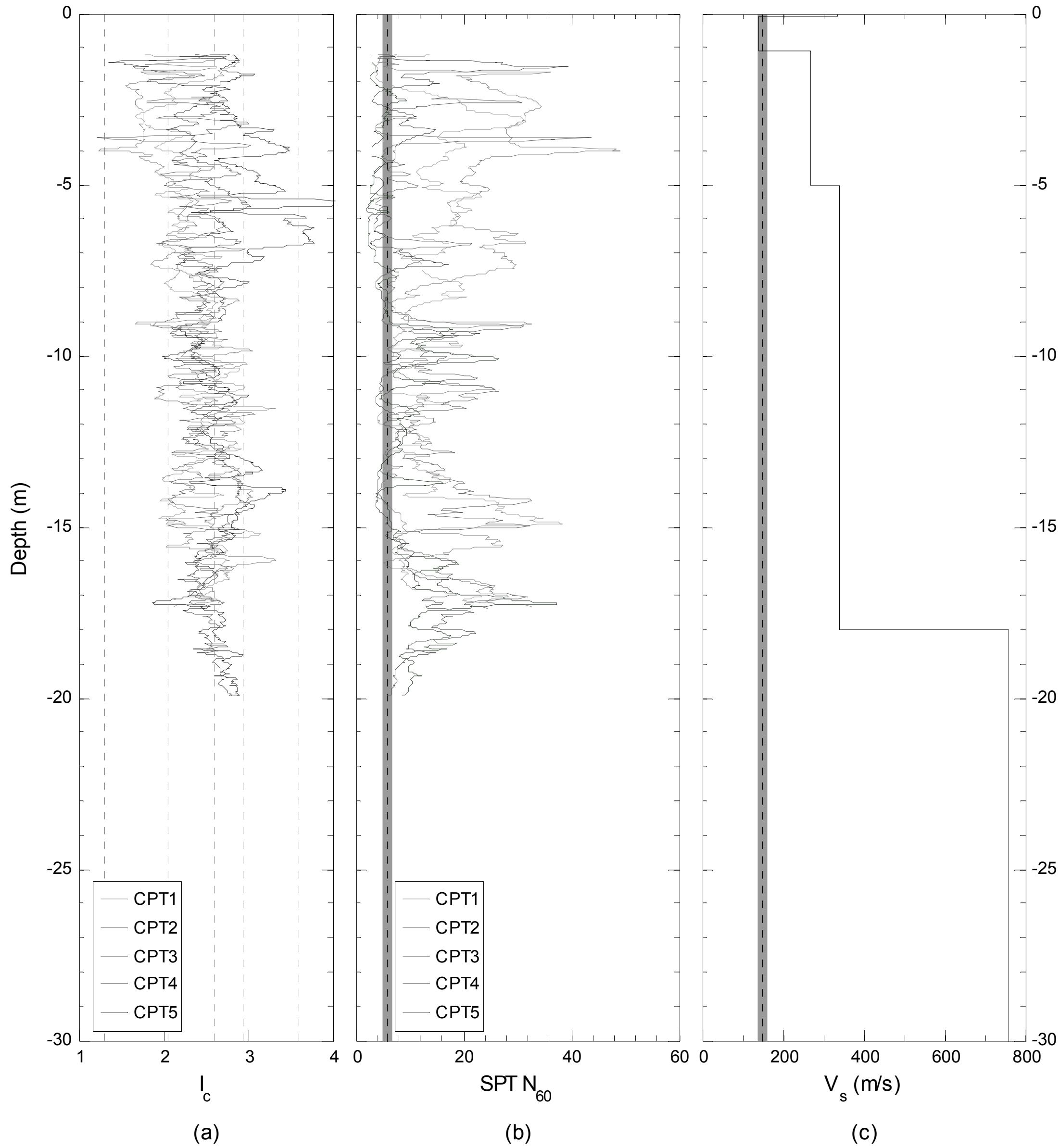


Figure 12 HVSC geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.8 Kaiapoi North School (KPOC)

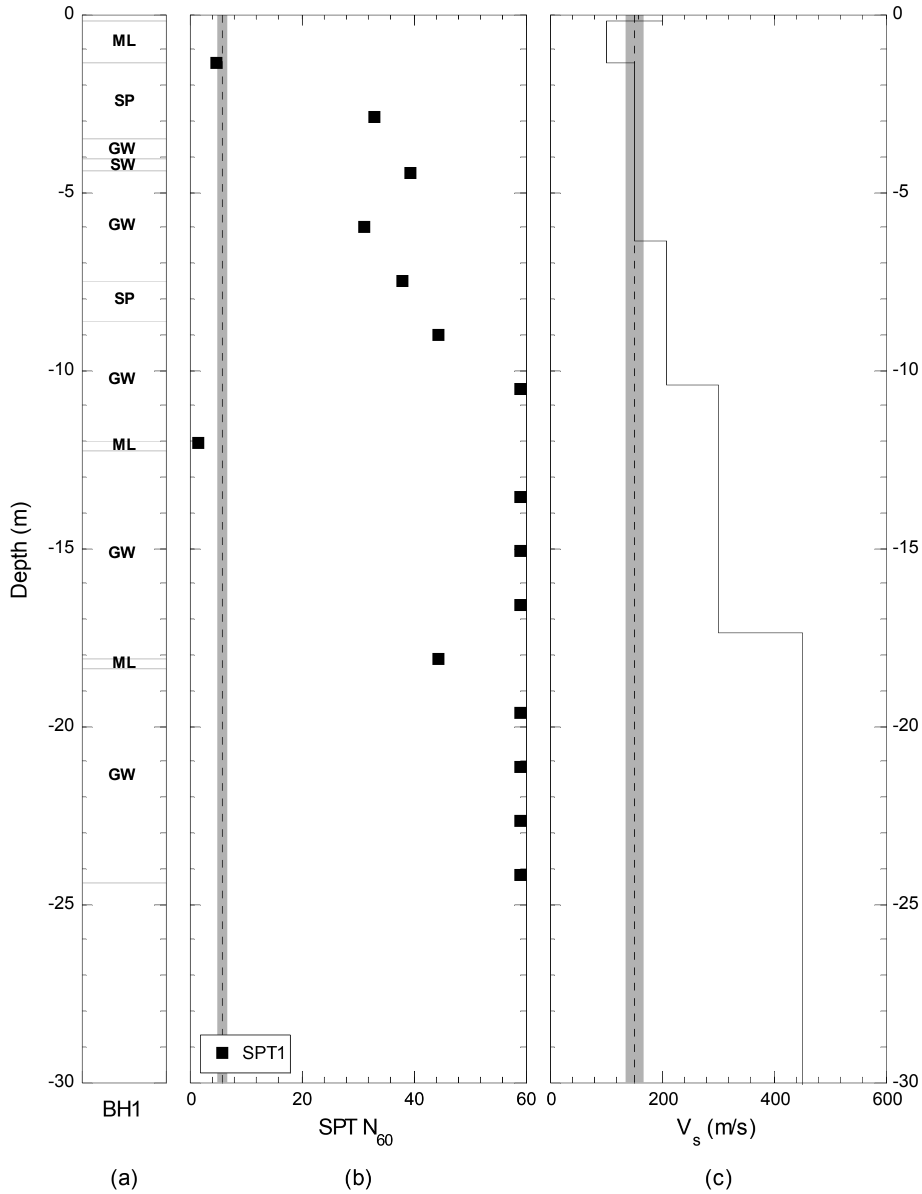


Figure 13 KPOC geotechnical site investigation summary (a) borehole BH1 log, (b) SPT blow counts, (c) shear wave velocity

A.9 New Brighton Library (NBLC)

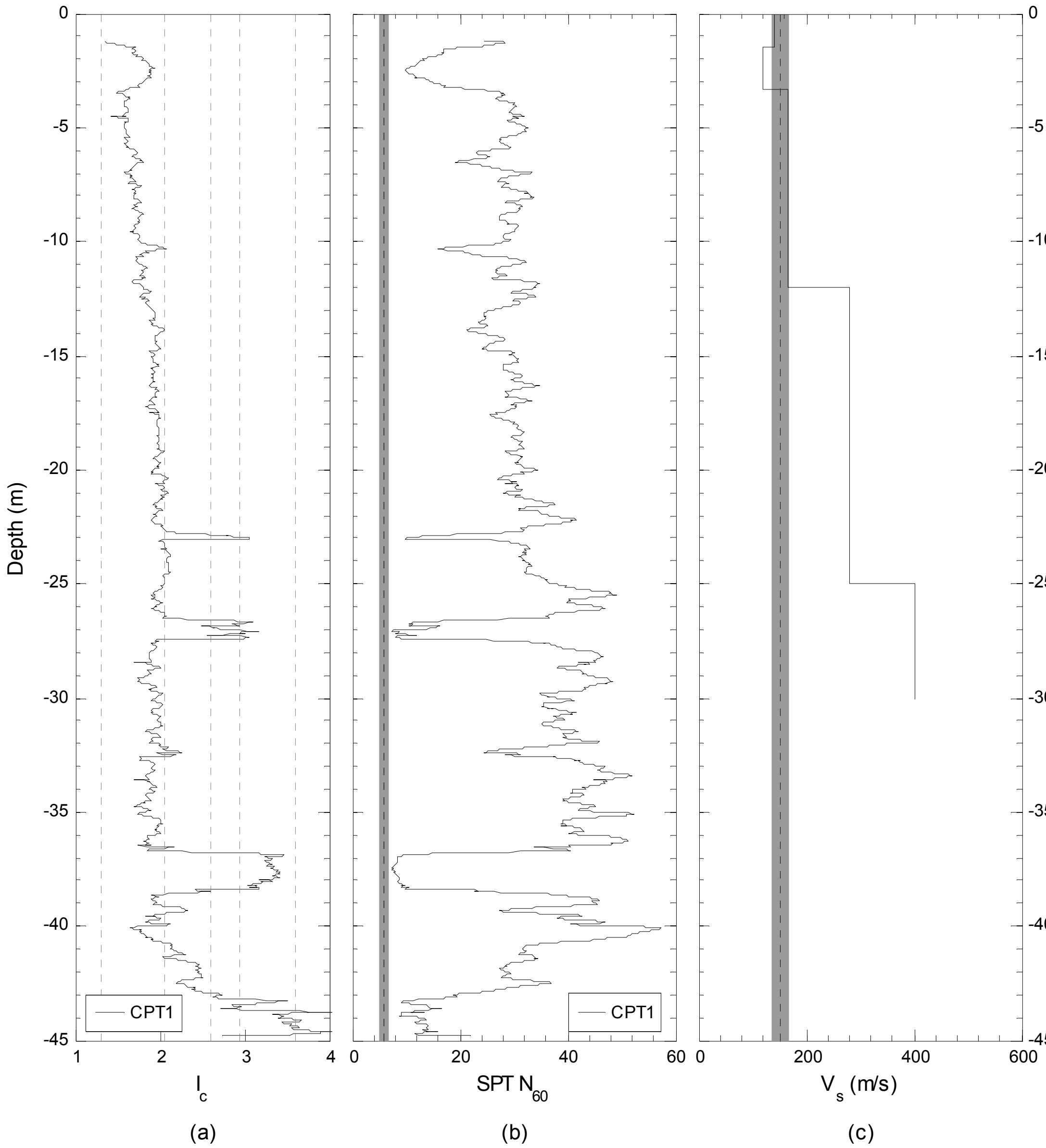


Figure 14 NBLC geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.10 North New Brighton School (NNBS)

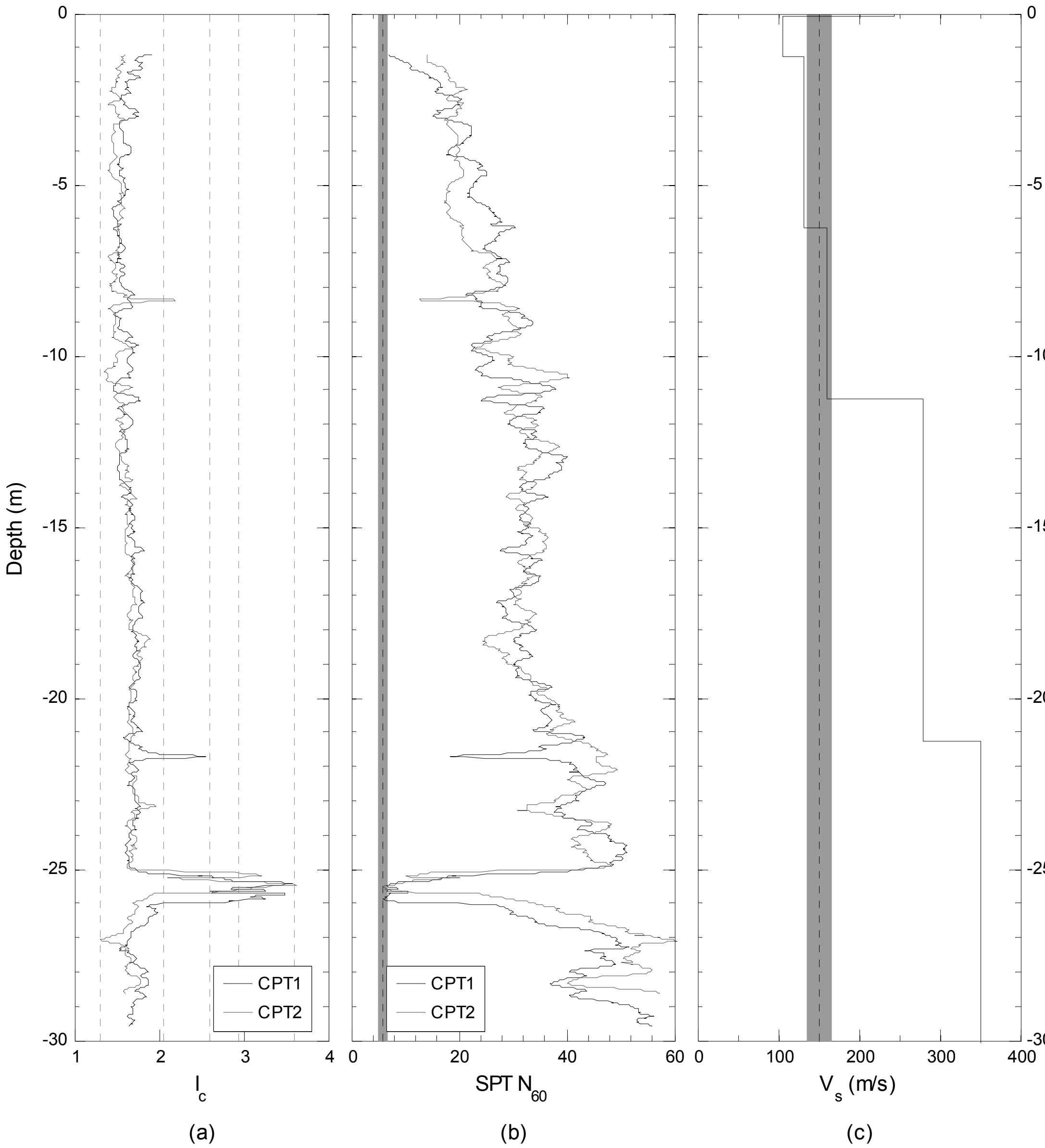


Figure 15 NNBS geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.11 Papanui High School (PPHS)

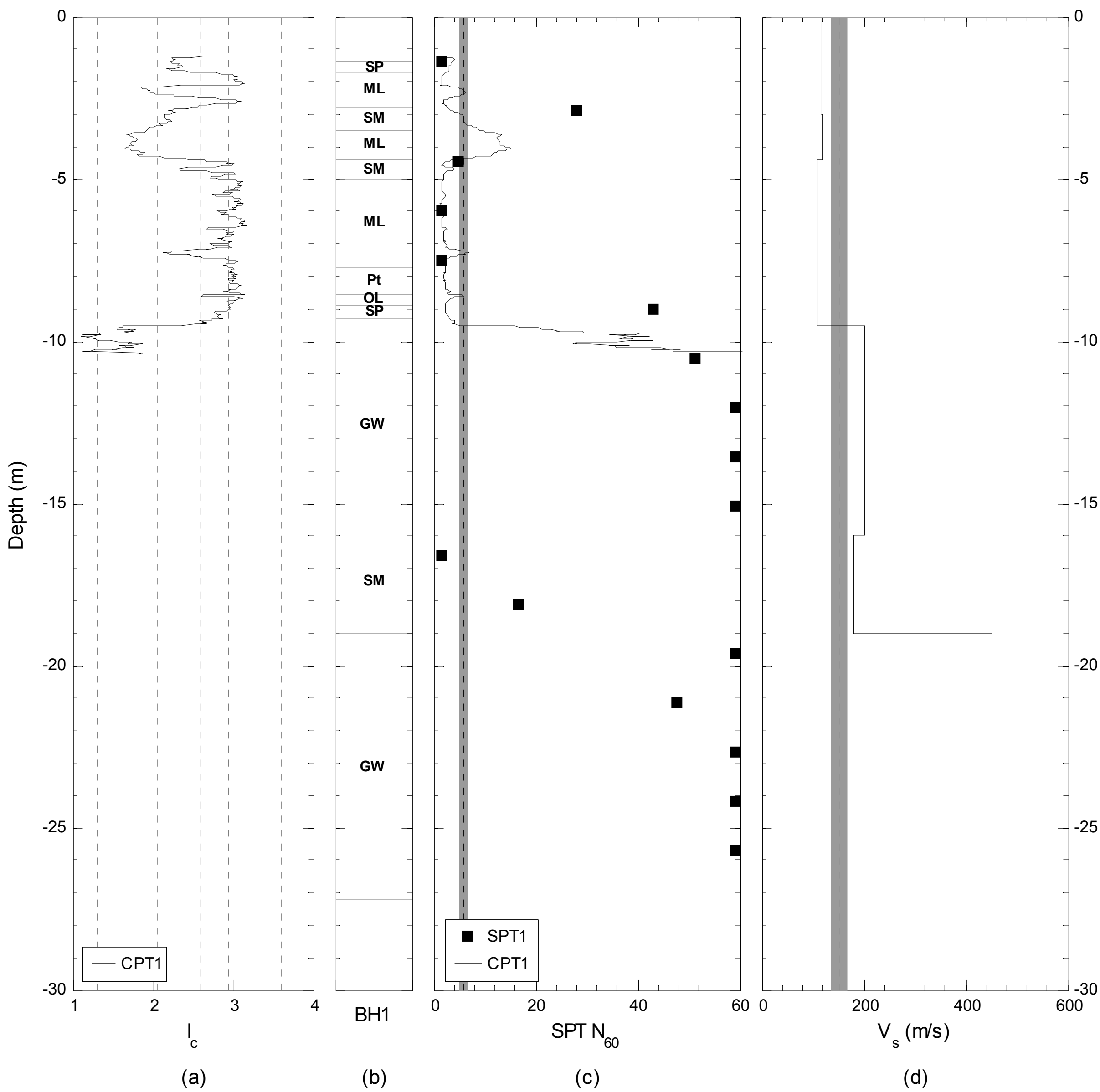


Figure 16 PPHS geotechnical site investigation summary (a) soil behaviour type index, (b) borehole BH1 log, (c) SPT blow counts, (d) shear wave velocity

A.12 Pages Road Pumping Station (PRPC)

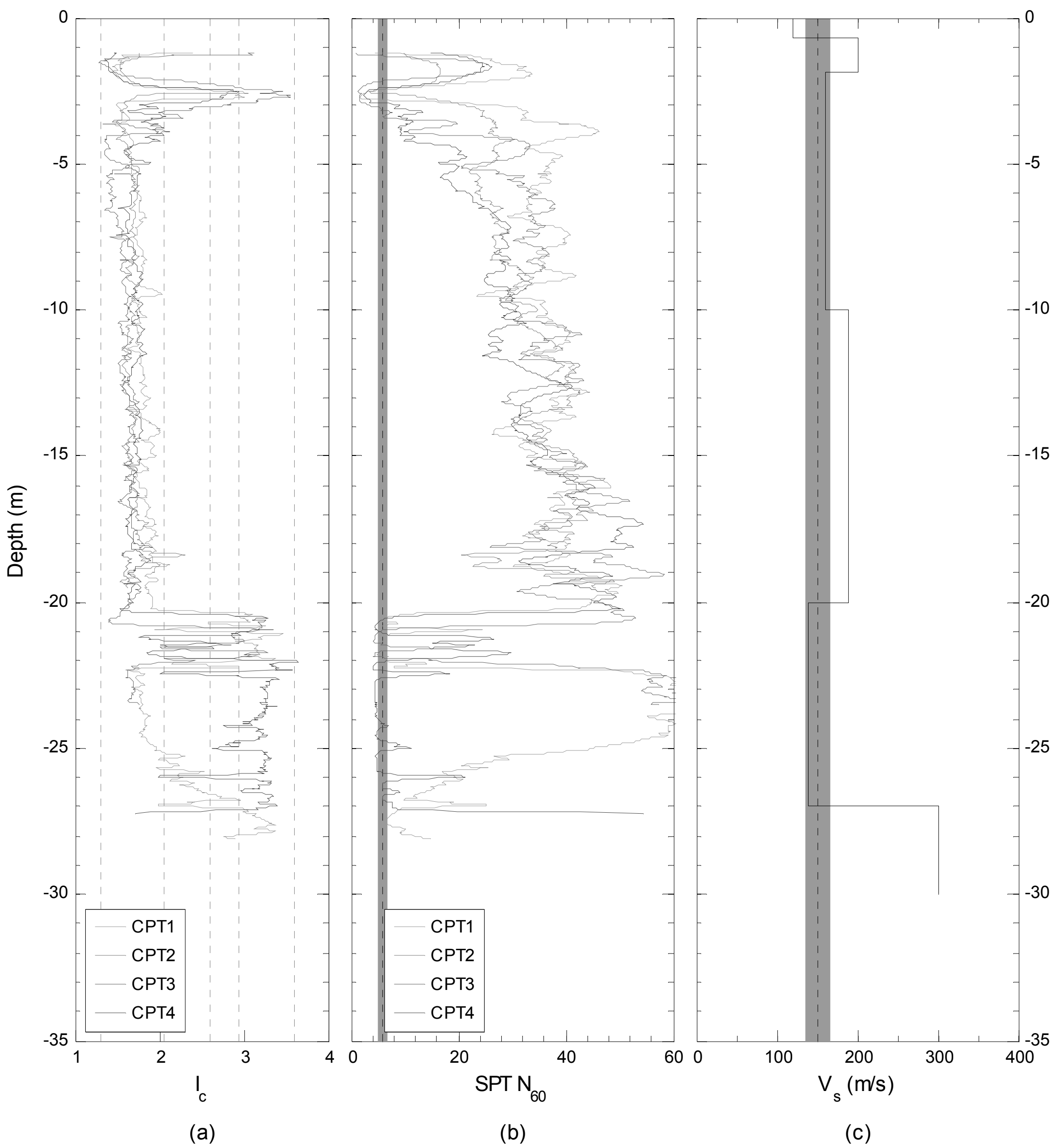


Figure 17 PRPC geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.13 Christchurch Resthaven (REHS)

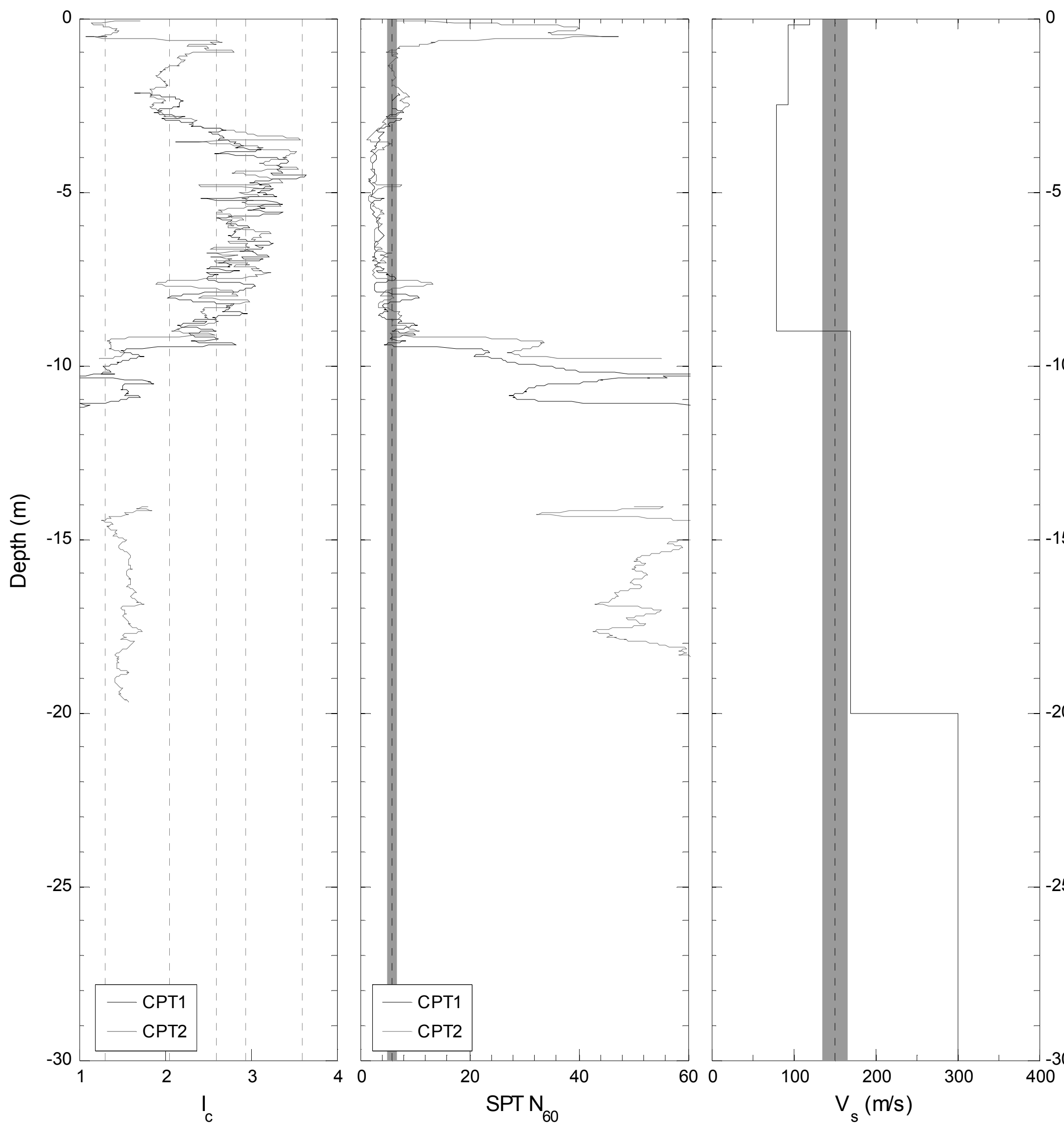


Figure 18 REHS geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.14 Riccarton High School (RHSC)

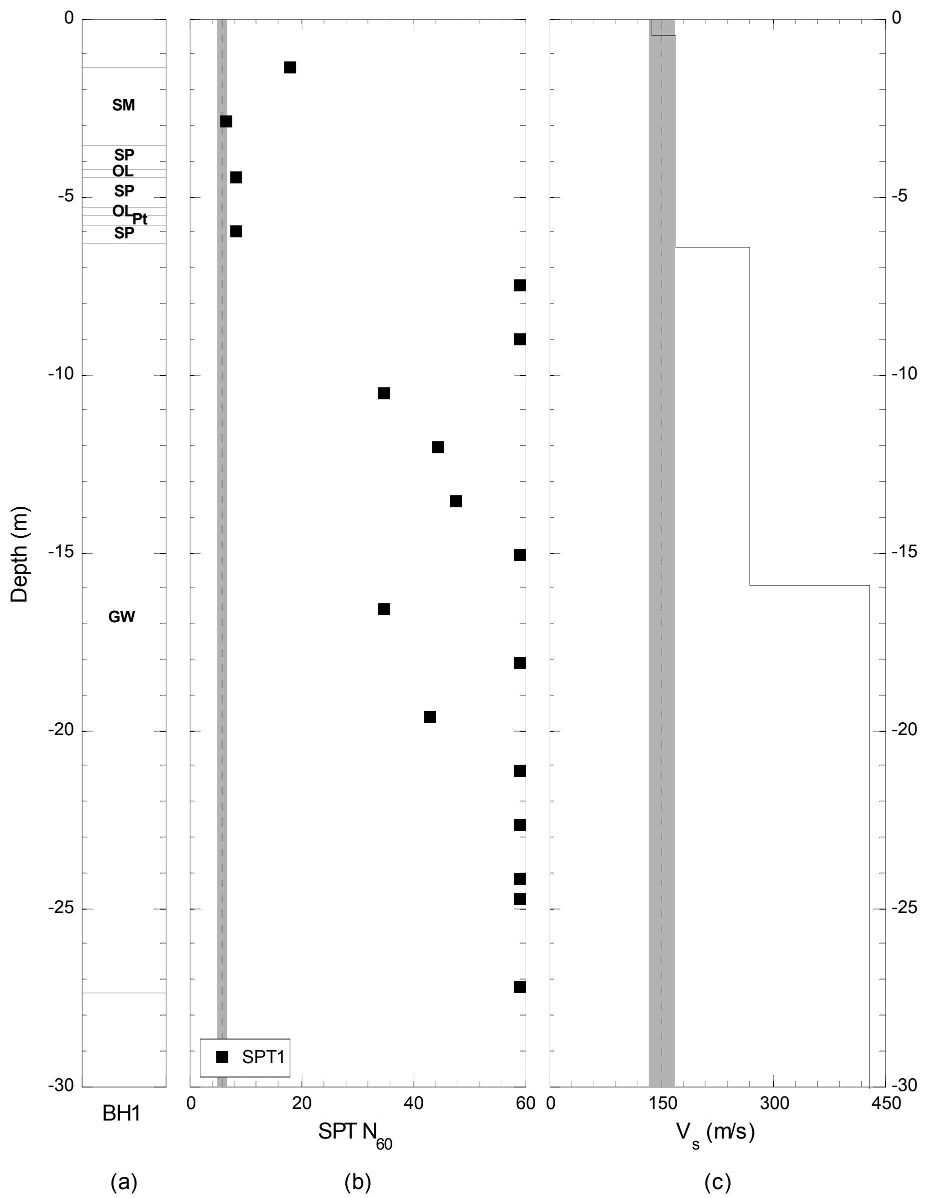


Figure 19 RHSC geotechnical site investigation summary (a) borehole BH1 log, (b) SPT blow counts, (c) shear wave velocity

A.15 Shirley Library (SHLC)

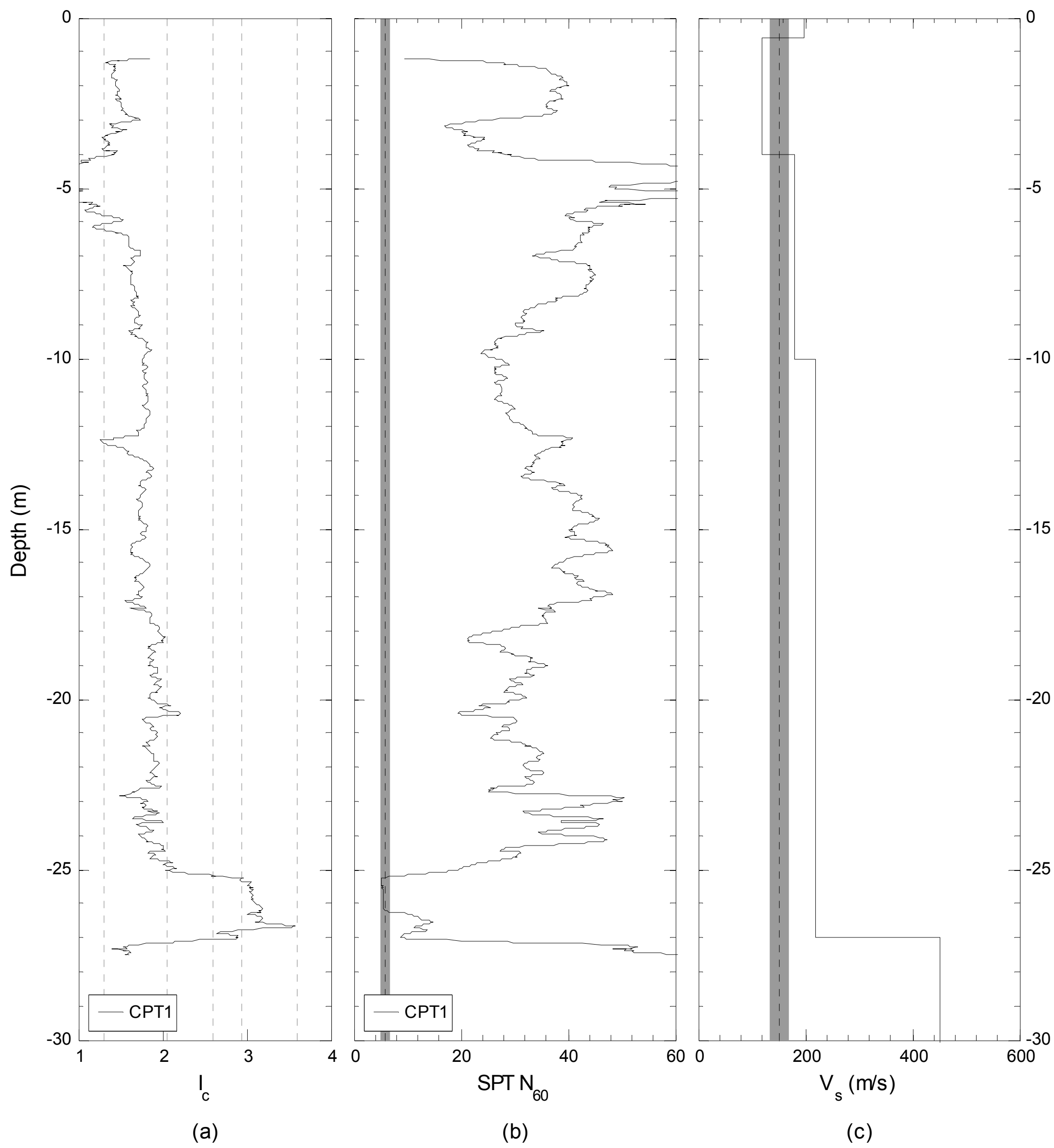


Figure 20 SHLC geotechnical site investigation summary (a) soil behaviour type index, (b) SPT blow counts, (c) shear wave velocity

A.16 Styx Mill Transfer Station (SMTC)

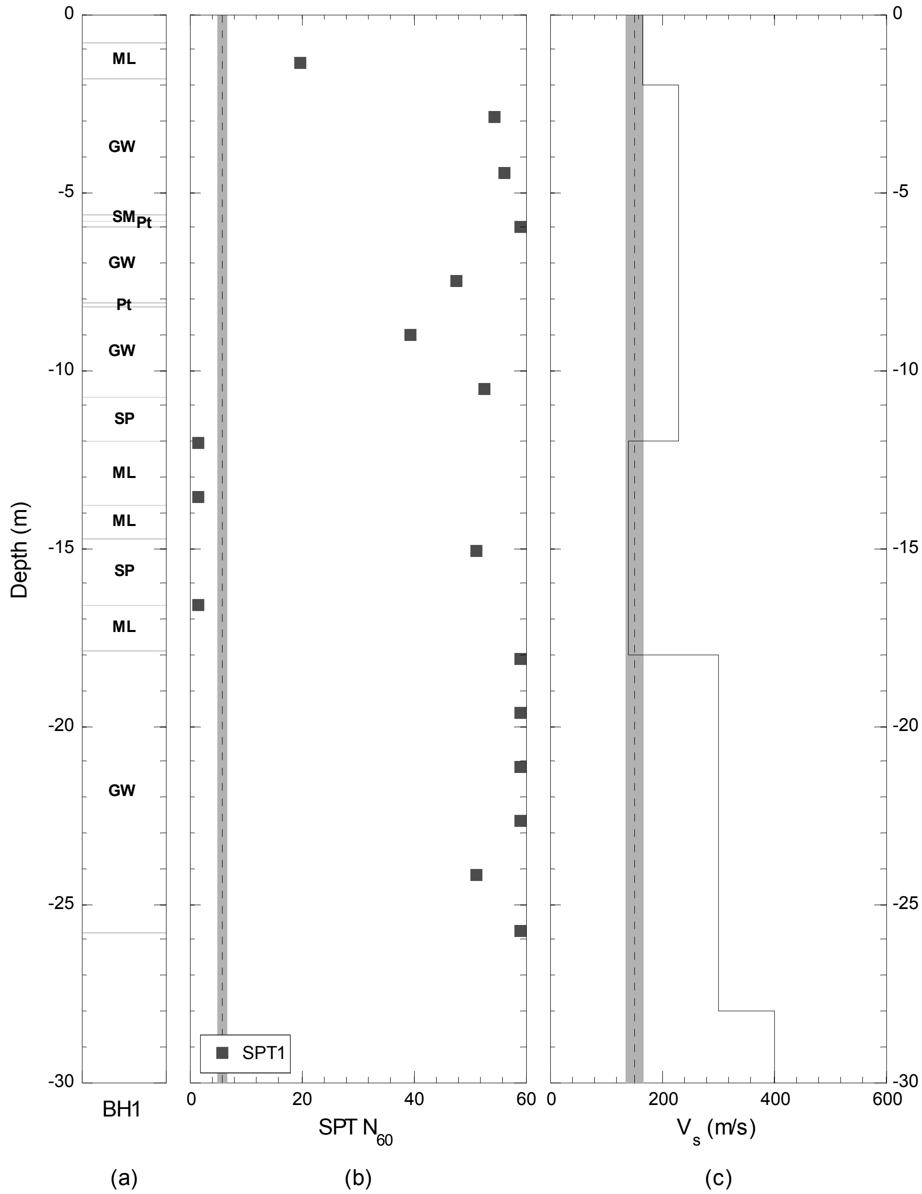


Figure 21 SMTC geotechnical site investigation summary (a) borehole BH1 log, (b) SPT blow counts, (c) shear wave velocity

Appendix B Liquefaction Triggering

This Appendix summarises the liquefaction triggering calculations for the Darfield and Christchurch earthquakes for those SMS locations not dominated by surface gravels.

B.1 Christchurch Botanical Gardens (CBGS)

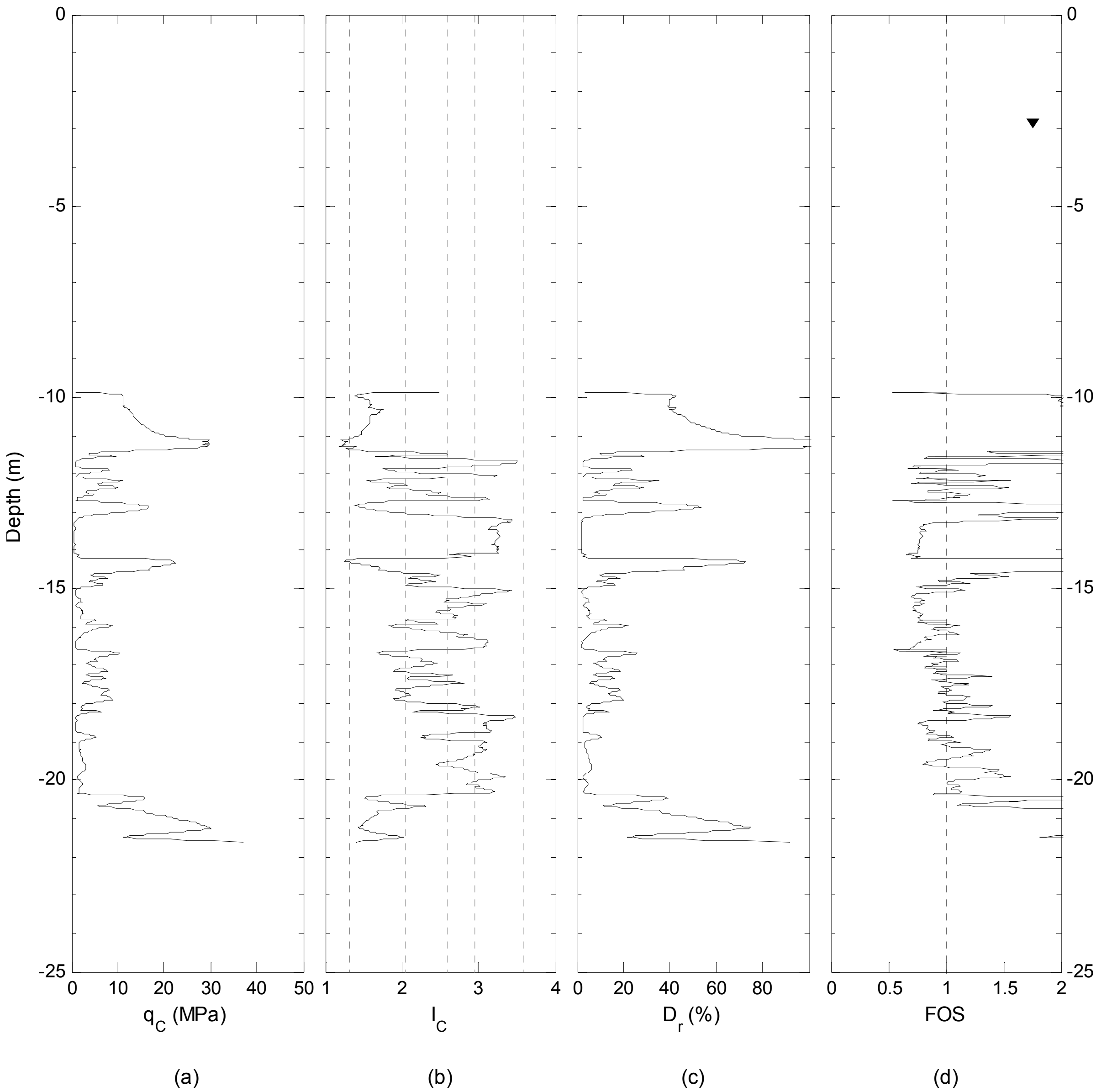


Figure 22 Summary of CPT liquefaction triggering calculations of the CBGS SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

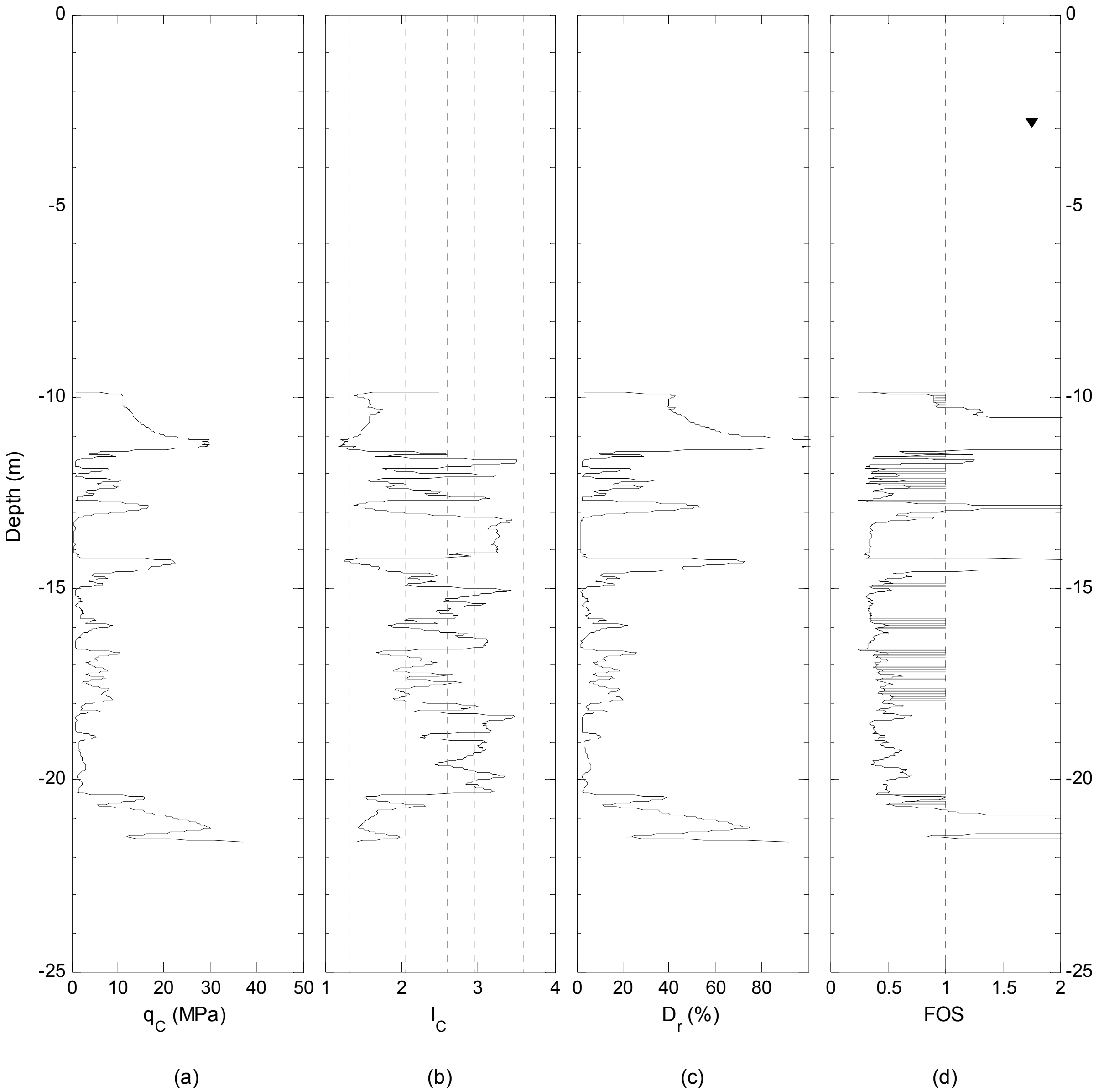


Figure 23 Summary of CPT liquefaction triggering calculations of the CBGS SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.2 Christchurch Cathedral College (CCCC)

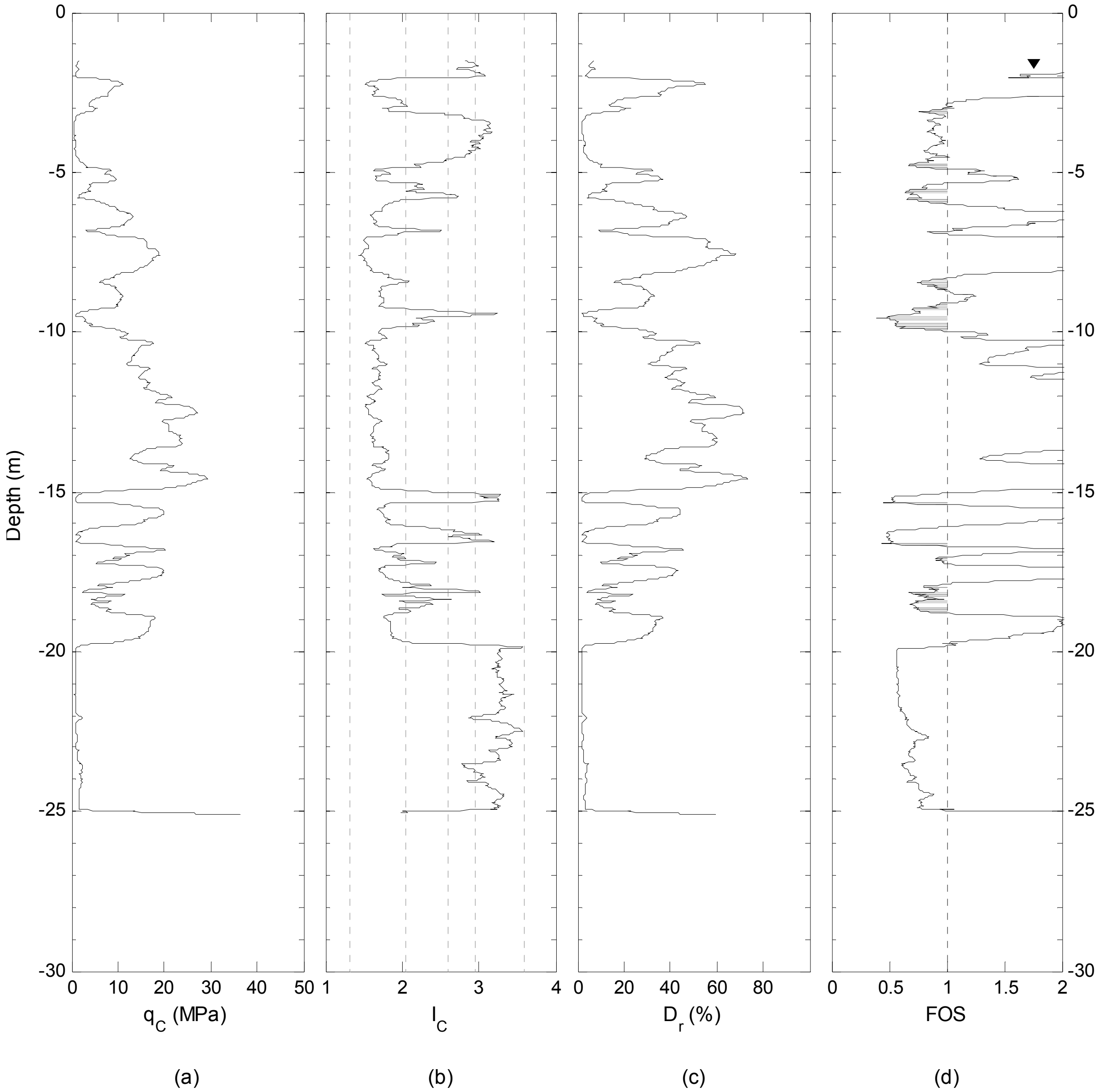


Figure 24 Summary of CPT liquefaction triggering calculations of the CCCC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

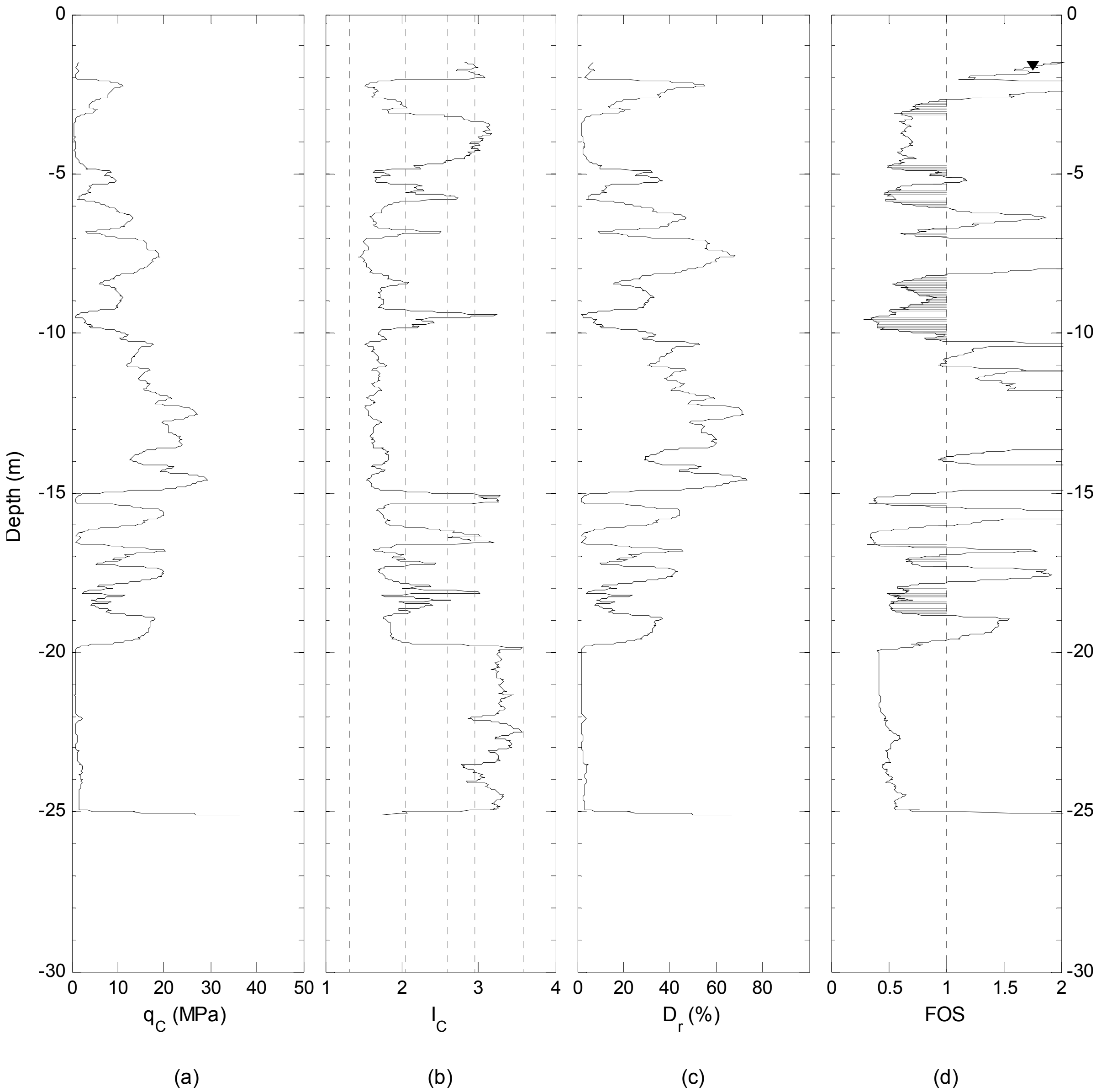


Figure 25 Summary of CPT liquefaction triggering calculations of the CCCC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.3 Christchurch Hospital (CHHC)

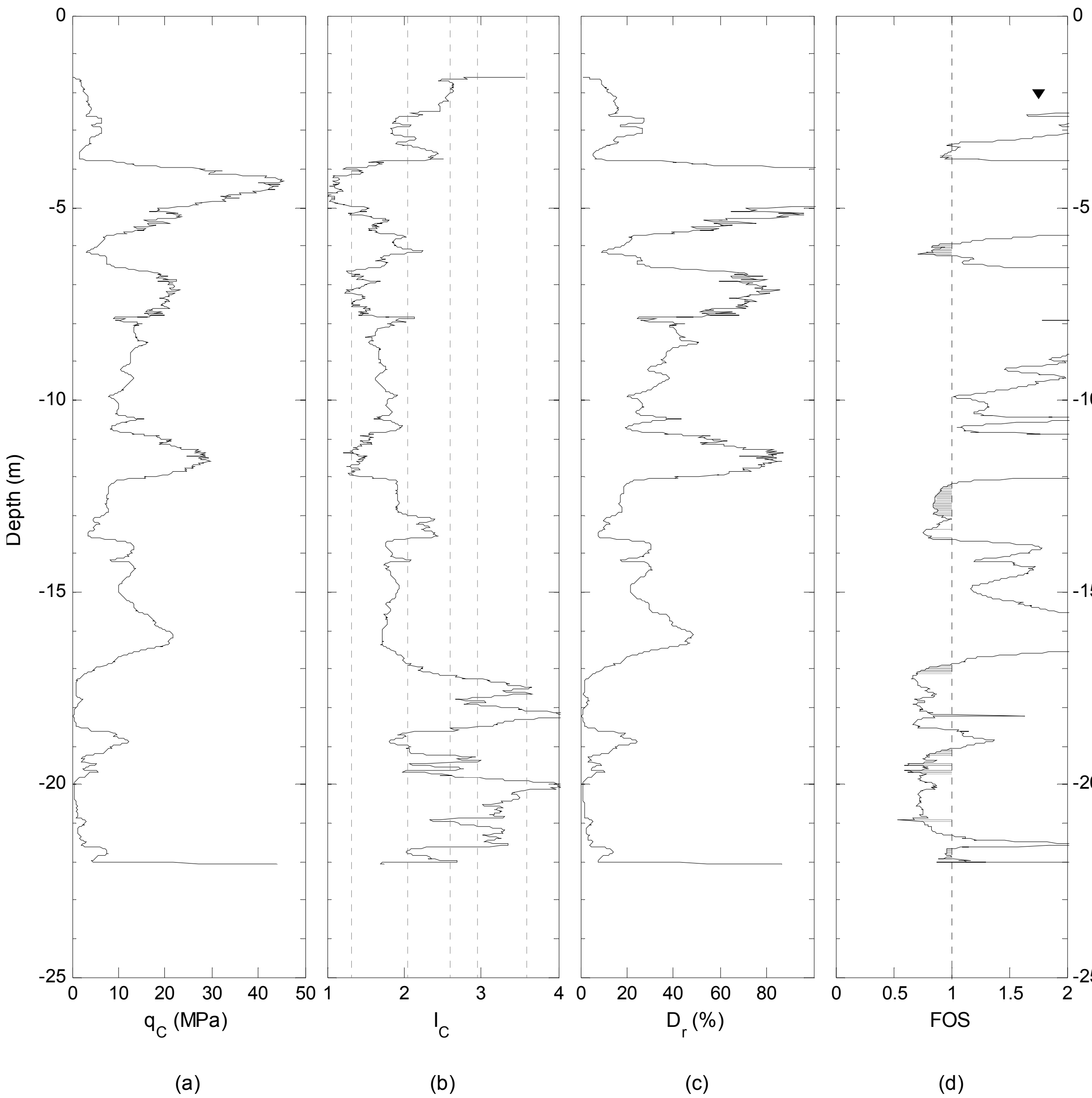


Figure 26 Summary of CPT liquefaction triggering calculations of the CHHC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

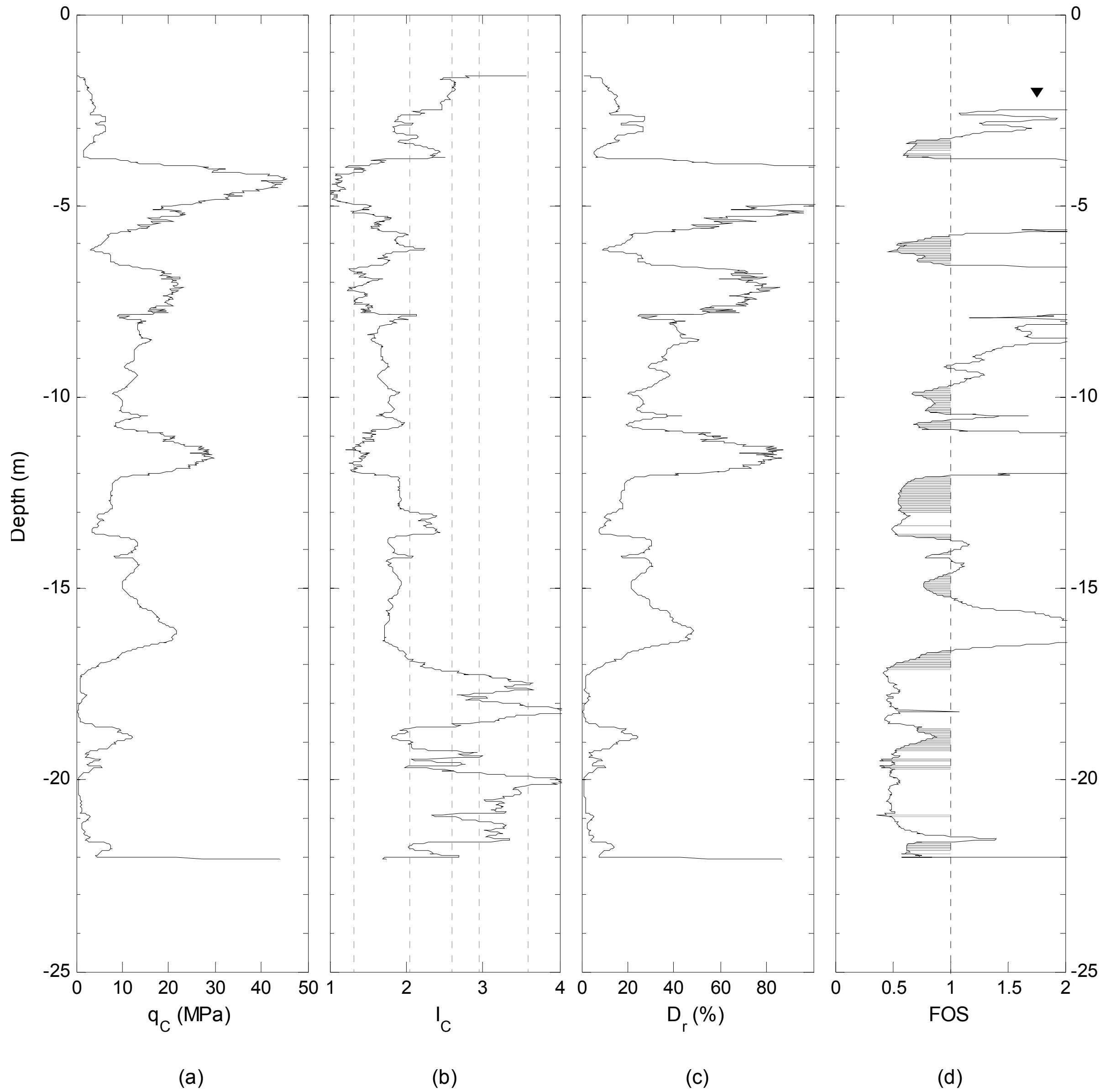


Figure 27 Summary of CPT liquefaction triggering calculations of the CHHC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.4 Cashmere High School (CMHS)

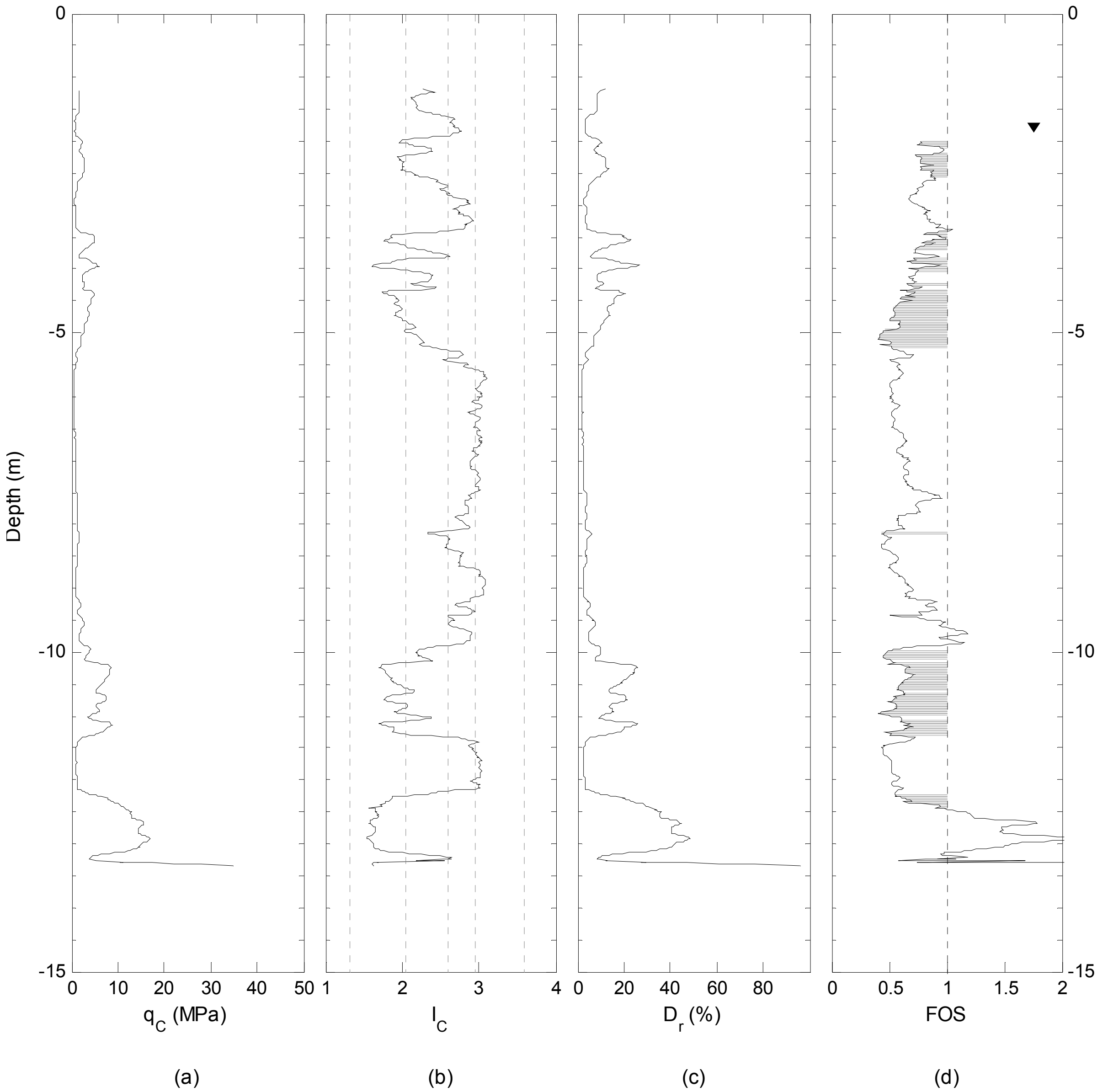


Figure 28 Summary of CPT liquefaction triggering calculations of the CMHS SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

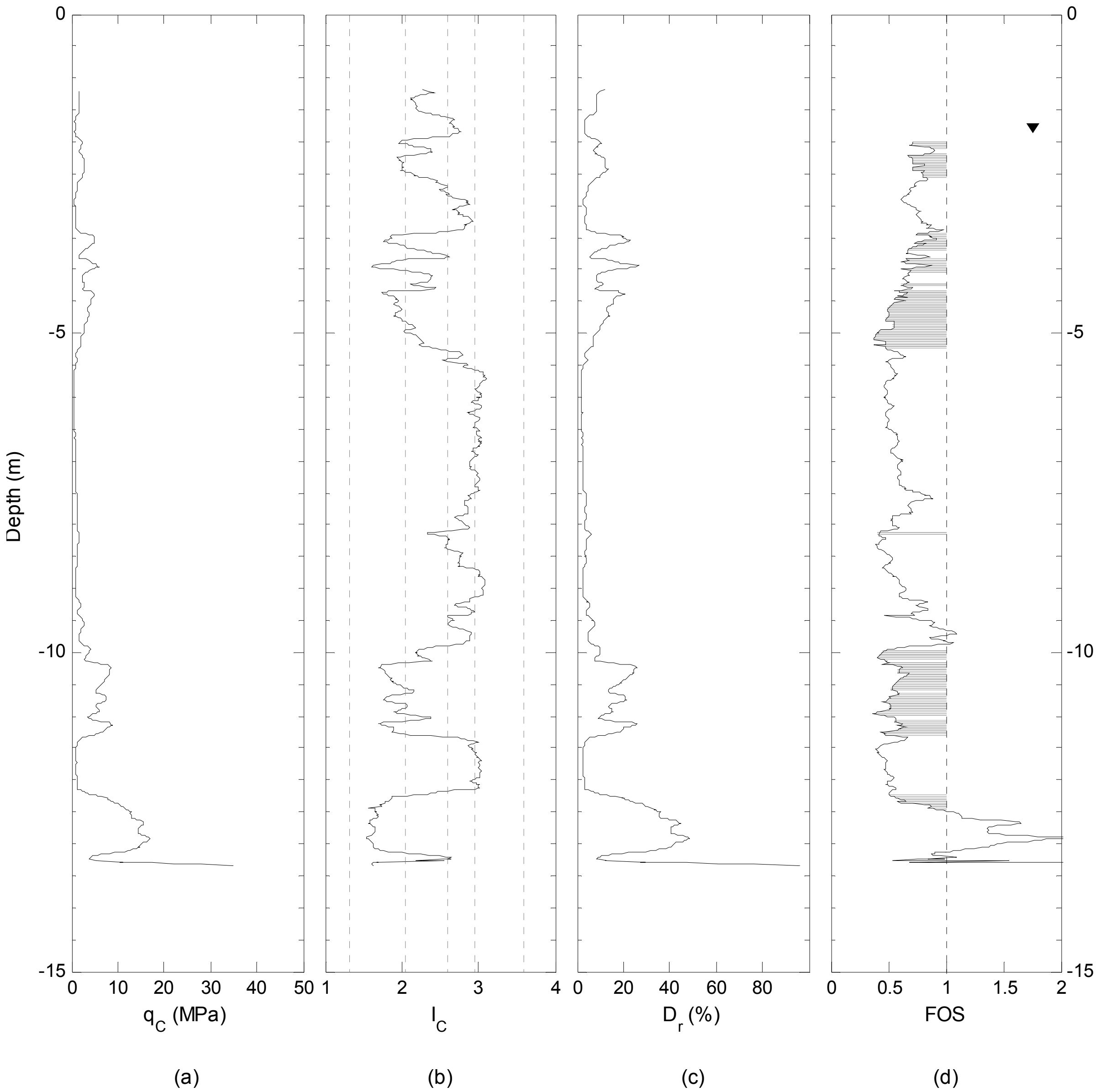


Figure 29 Summary of CPT liquefaction triggering calculations of the CMHS SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.5 Hulverstone Drive Pumping Station (HPSC)

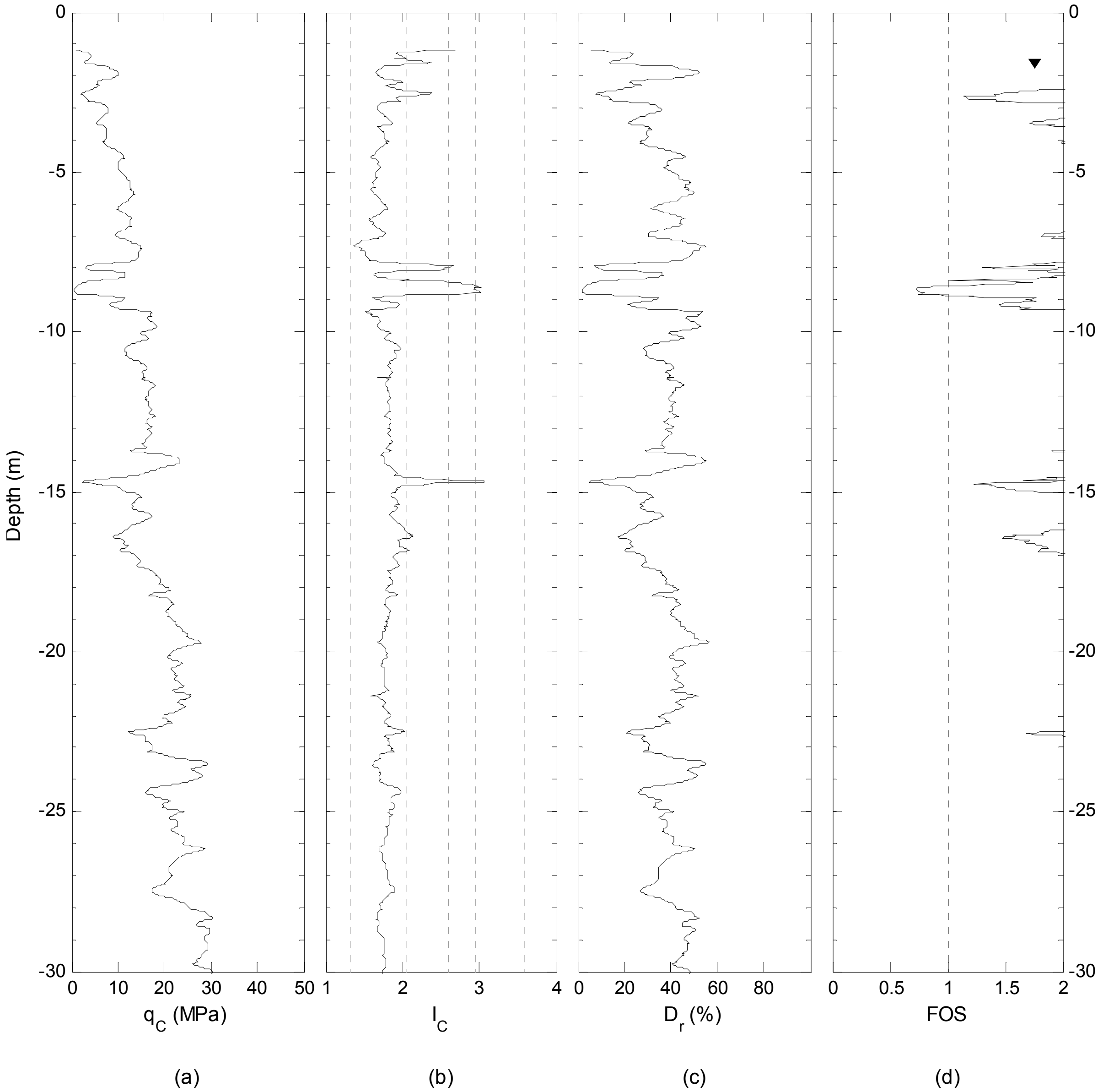


Figure 30 Summary of CPT liquefaction triggering calculations of the HPSC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

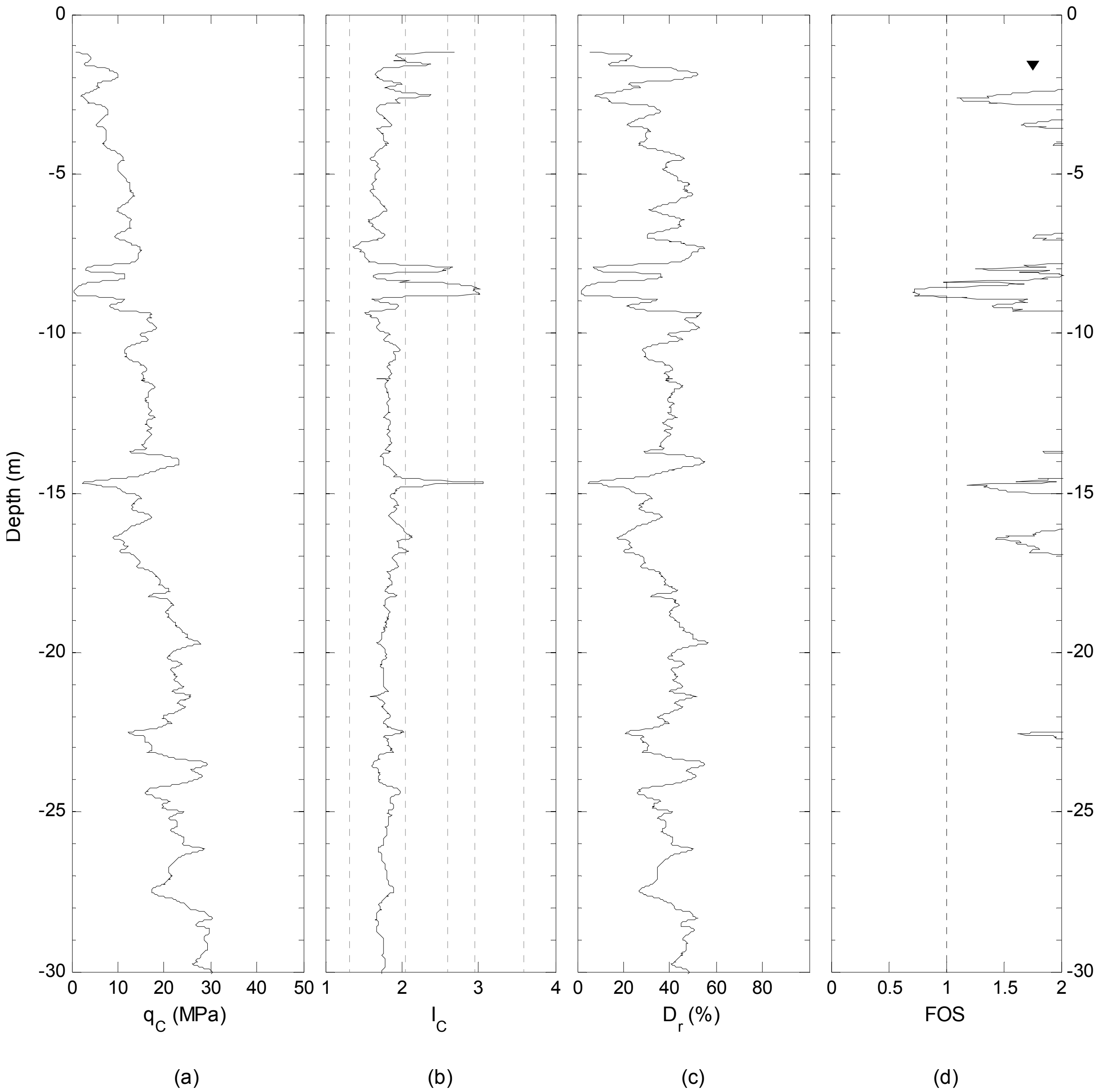


Figure 31 Summary of CPT liquefaction triggering calculations of the HPSC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.6 Heathcote Valley Primary School (HVSC)

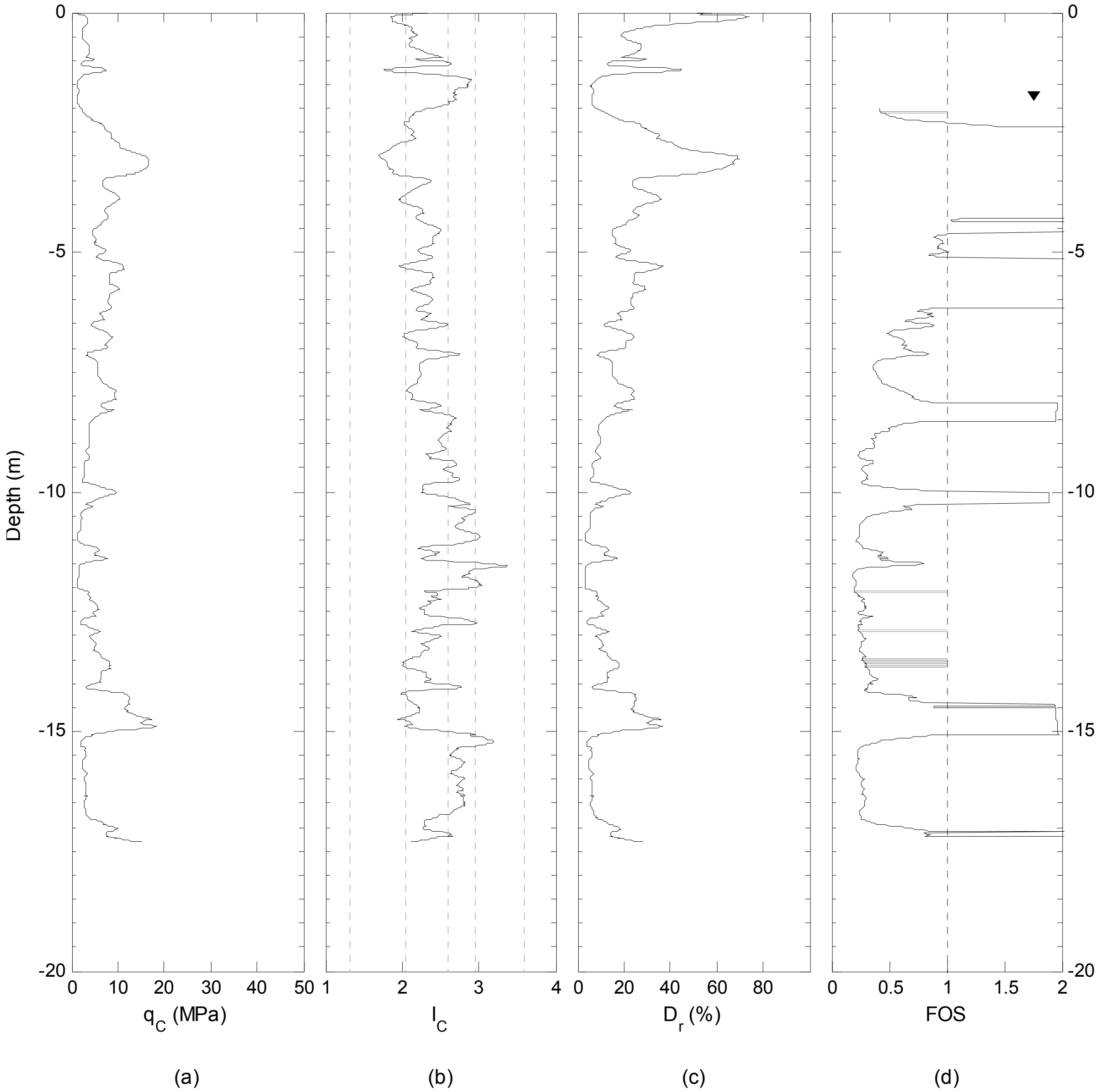


Figure 32 Summary of CPT liquefaction triggering calculations of the HVSC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

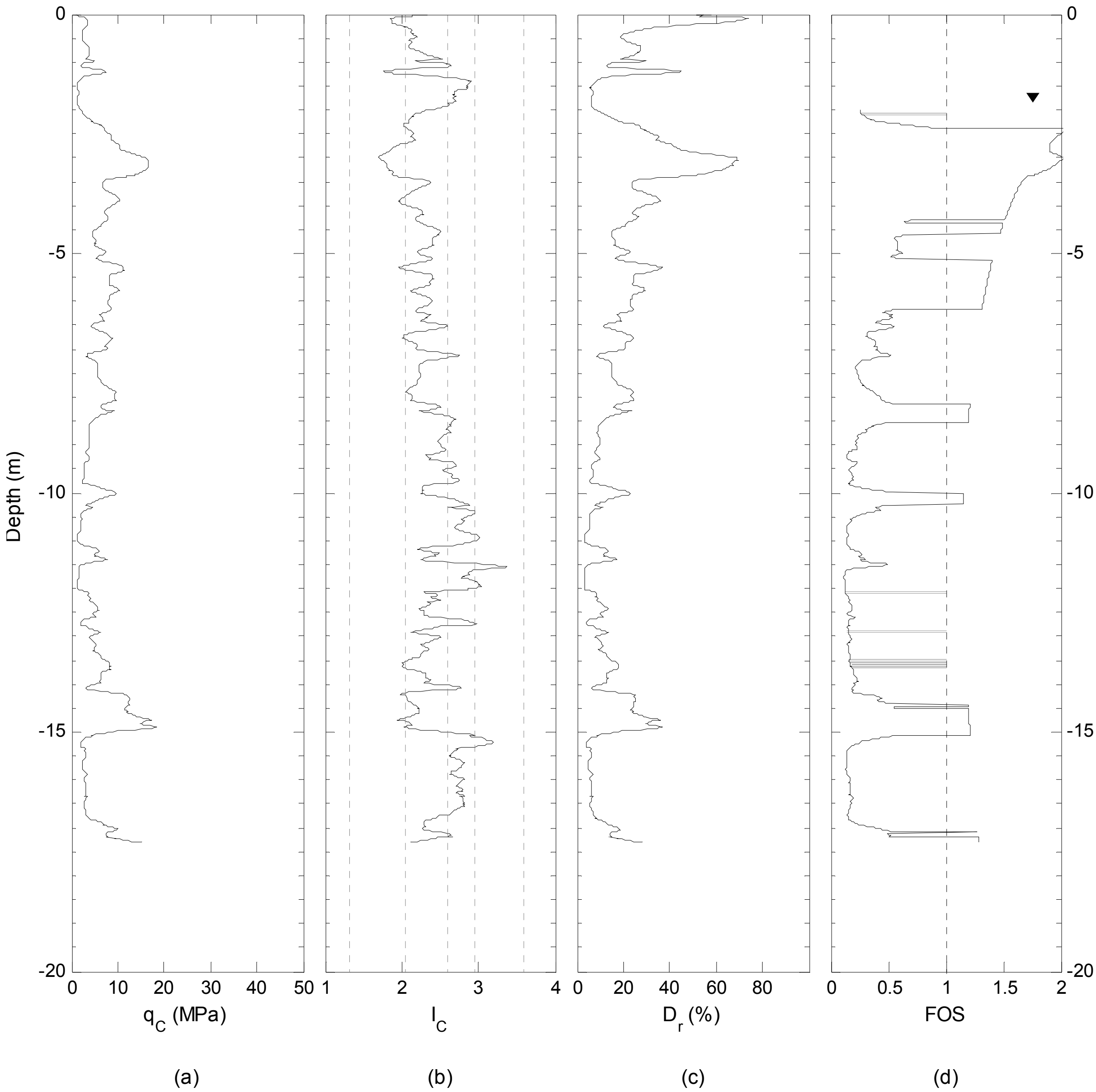


Figure 33 Summary of CPT liquefaction triggering calculations of the HVSC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.7 New Brighton Library (NBLC)

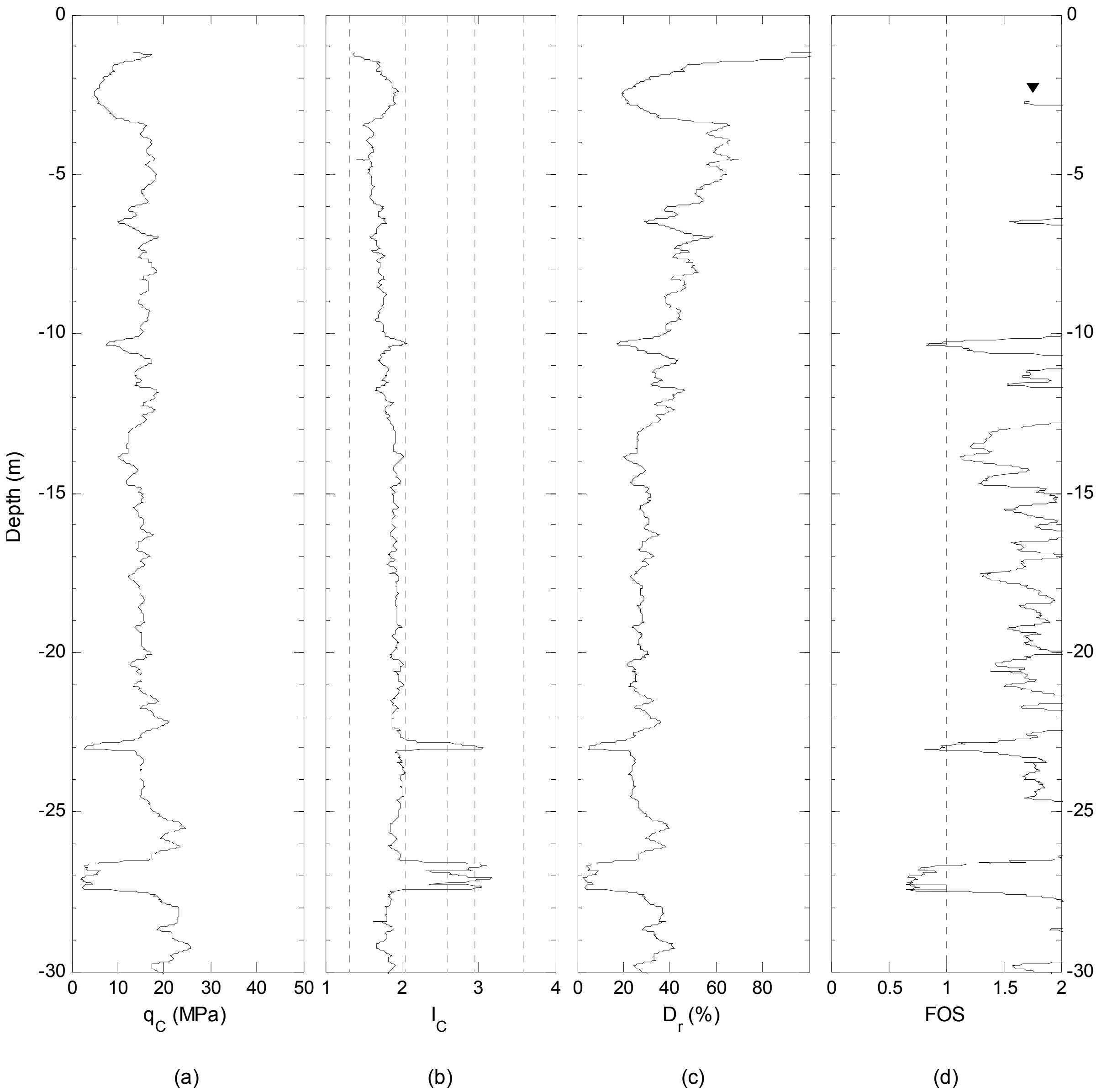


Figure 34 Summary of CPT liquefaction triggering calculations of the NBLC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

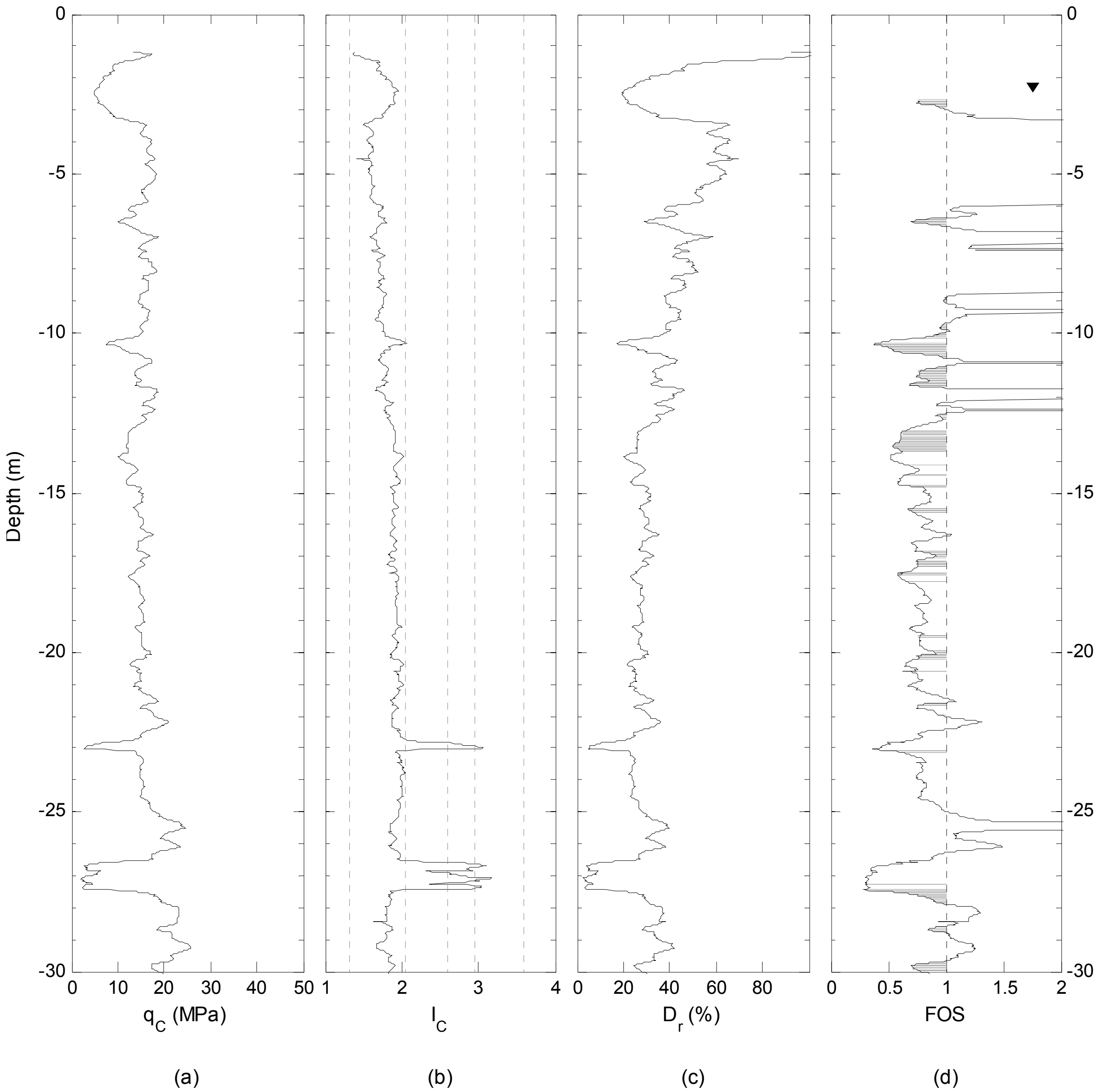


Figure 35 Summary of CPT liquefaction triggering calculations of the NBLC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.8 North New Brighton School (NNBS)

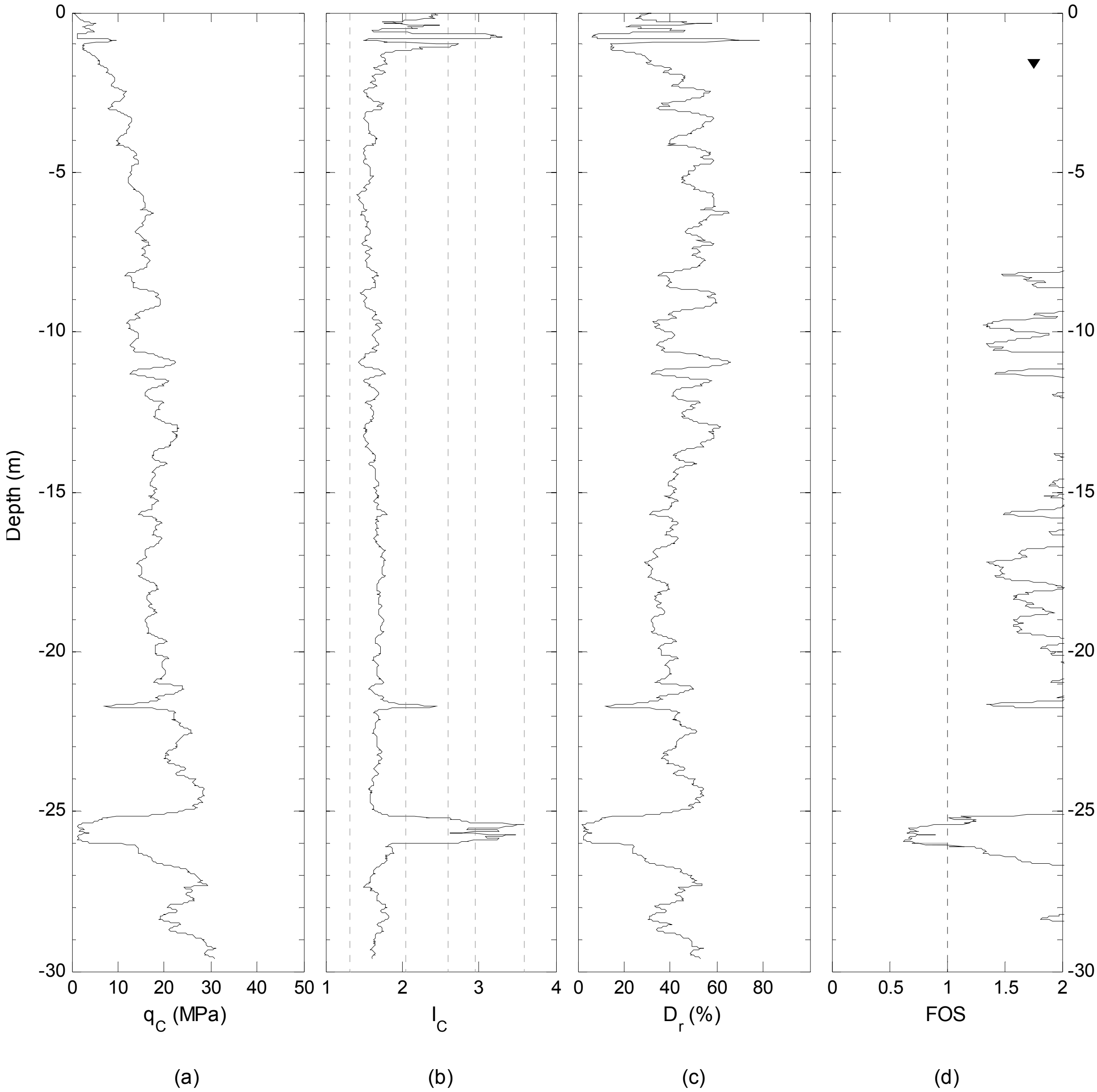


Figure 36 Summary of CPT liquefaction triggering calculations of the NNBS SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

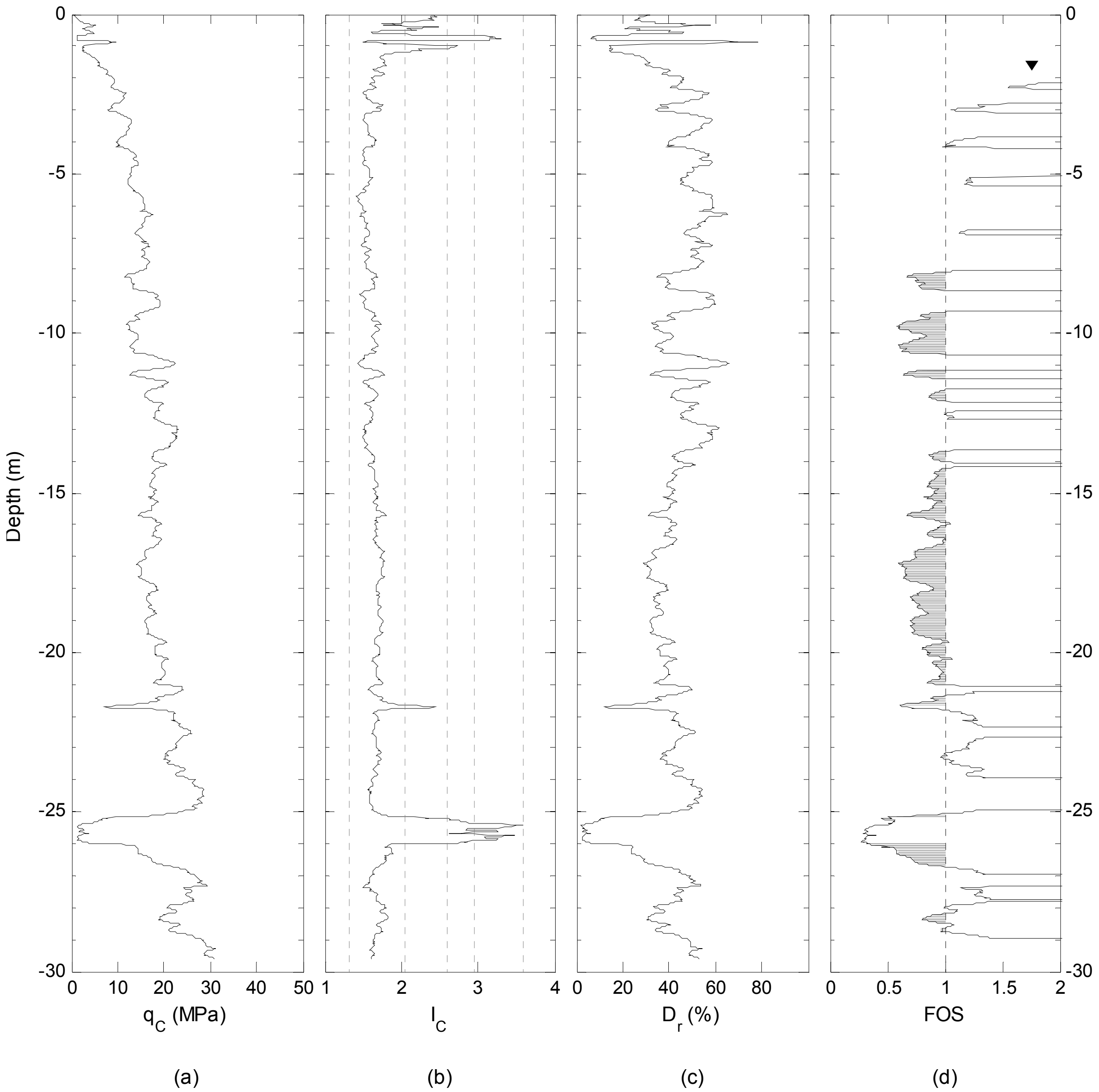


Figure 37 Summary of CPT liquefaction triggering calculations of the NNBS SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.9 Papanui High School (PPHS)

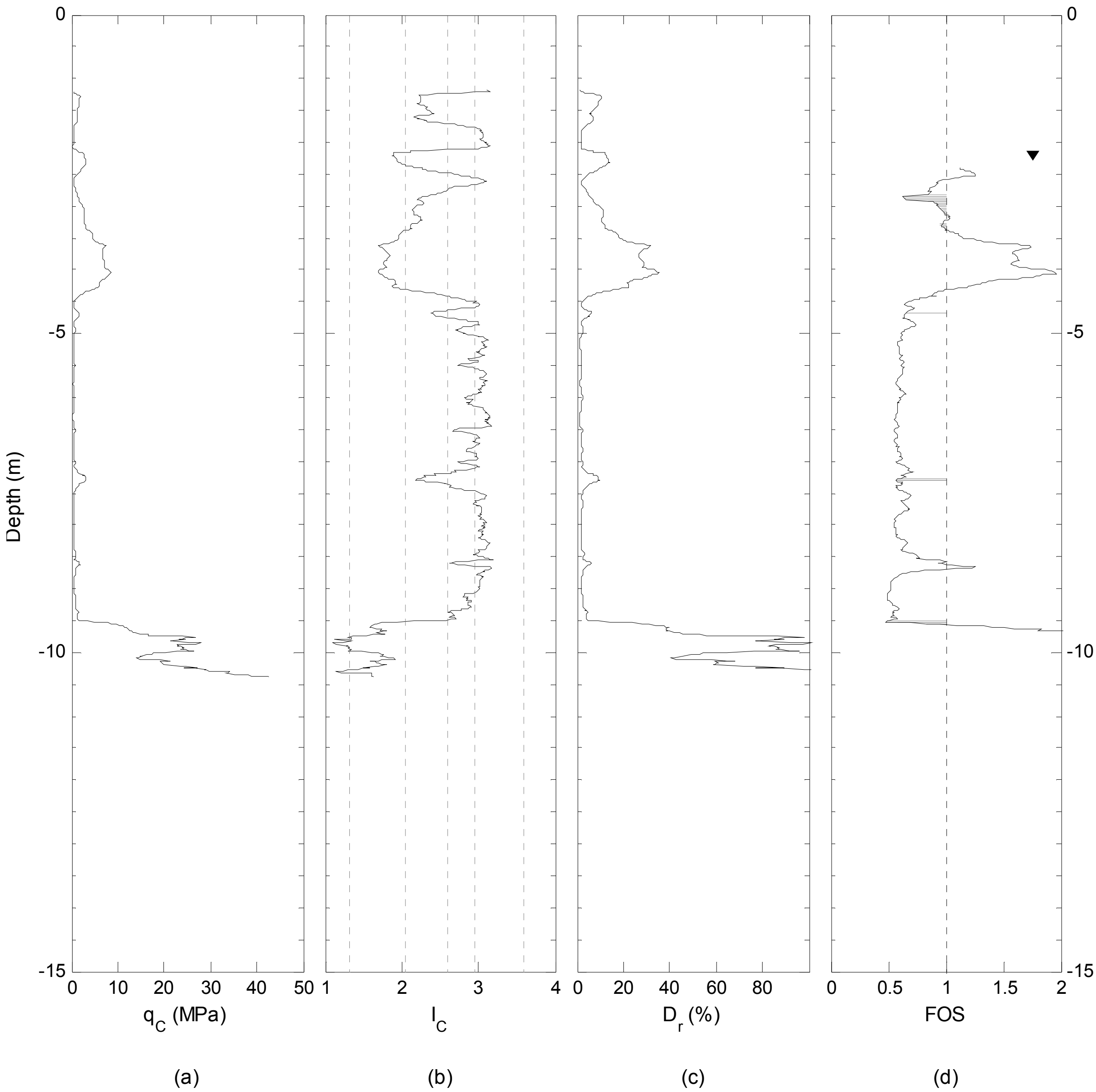


Figure 38 Summary of CPT liquefaction triggering calculations of the PPHS SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

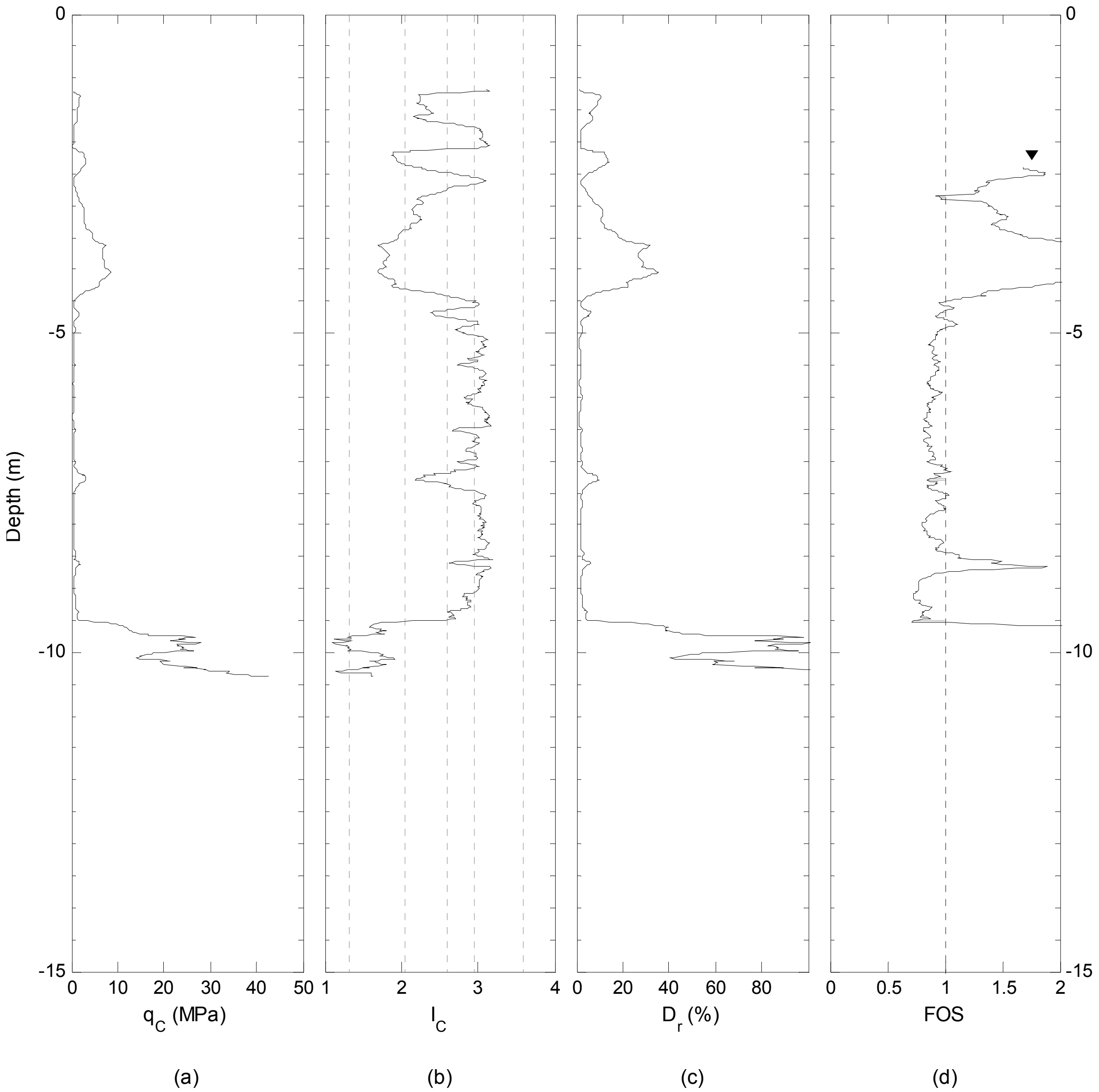


Figure 39 Summary of CPT liquefaction triggering calculations of the PPHS SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.10 Pages Road Pumping Station (PRPC)

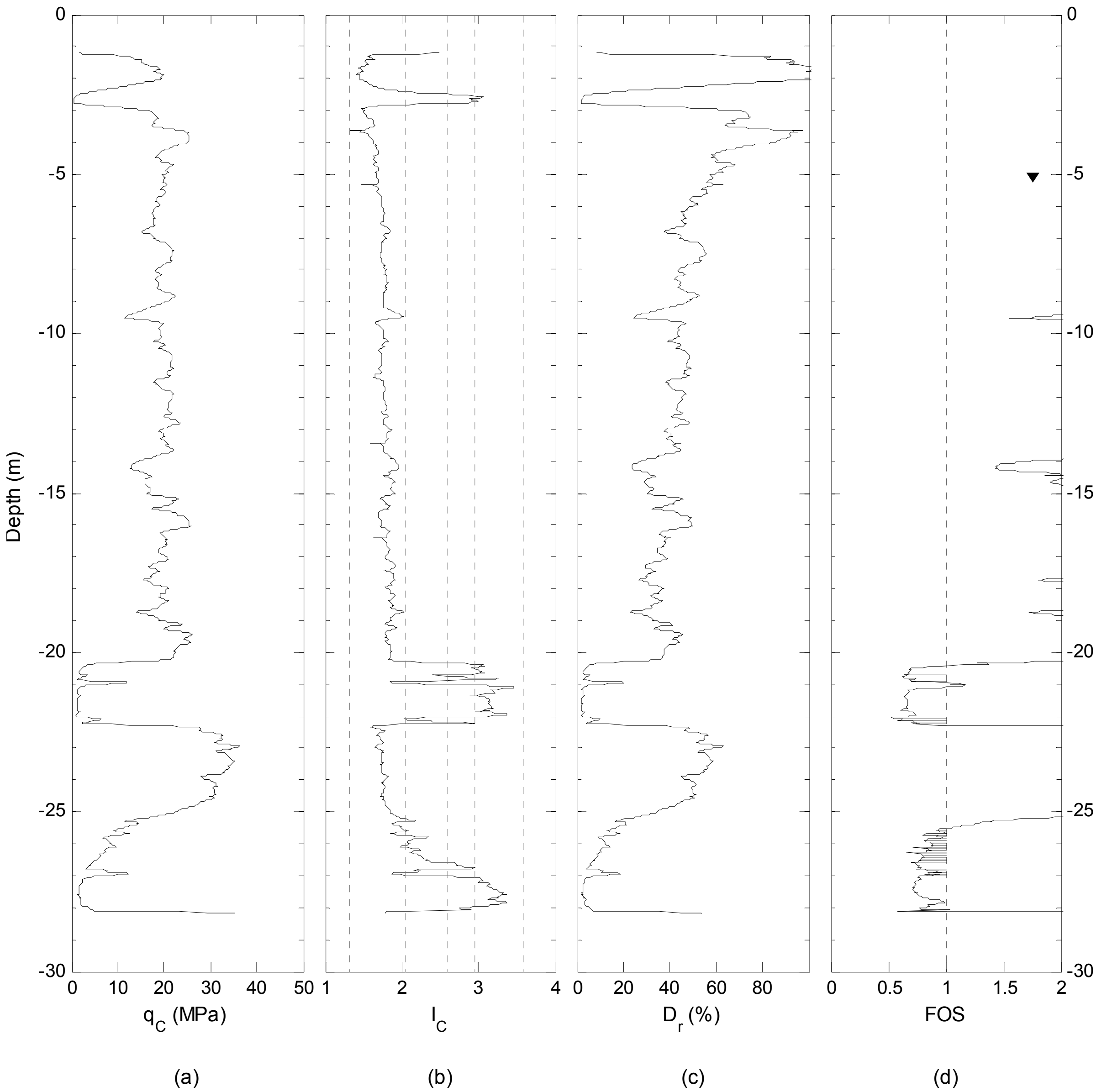


Figure 40 Summary of CPT liquefaction triggering calculations of the PRPC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

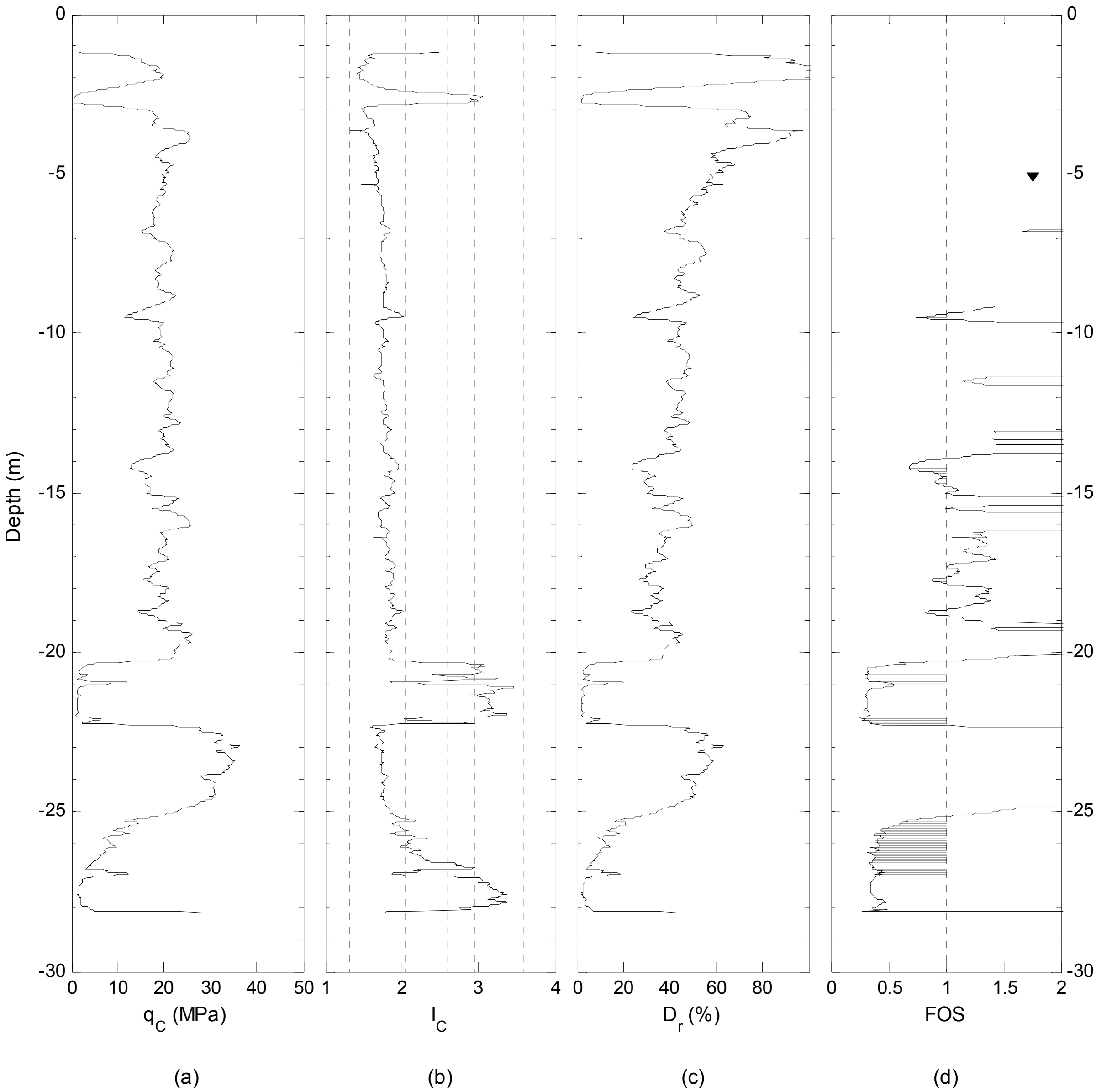


Figure 41 Summary of CPT liquefaction triggering calculations of the PRPC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.11 Christchurch Resthaven (REHS)

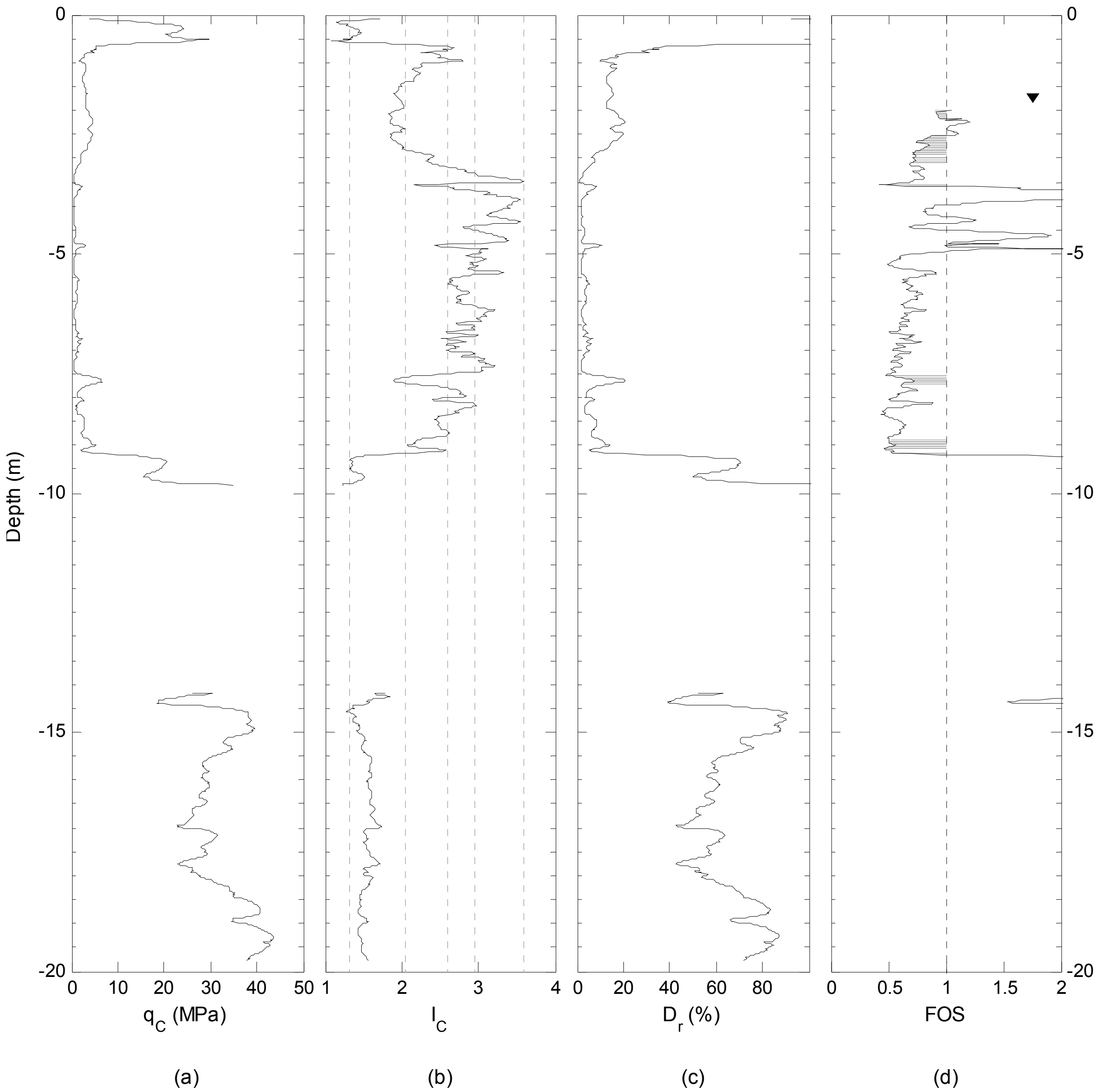


Figure 42 Summary of CPT liquefaction triggering calculations of the REHS SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

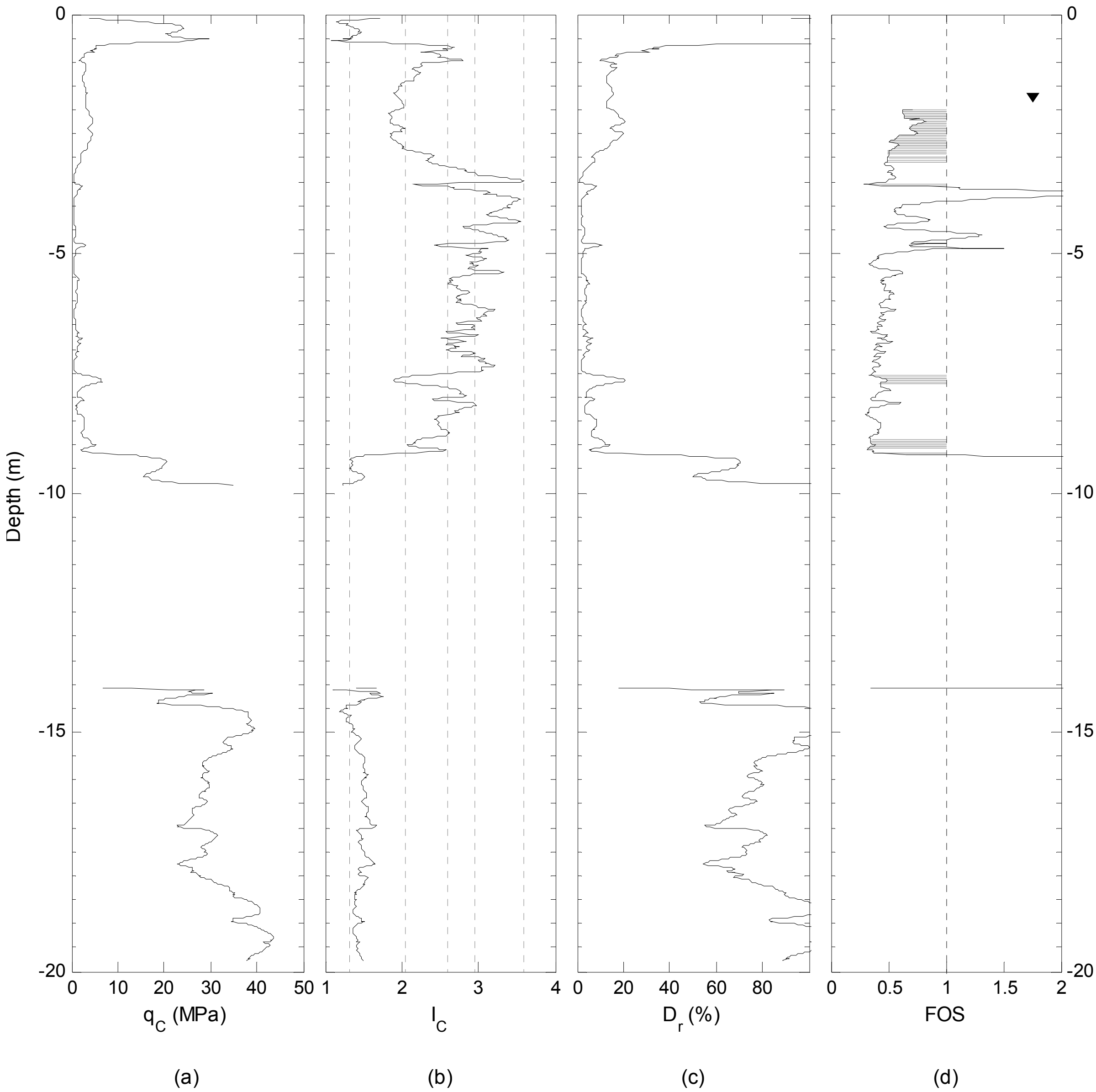


Figure 43 Summary of CPT liquefaction triggering calculations of the REHS SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

B.12 Shirley Library (SHLC)

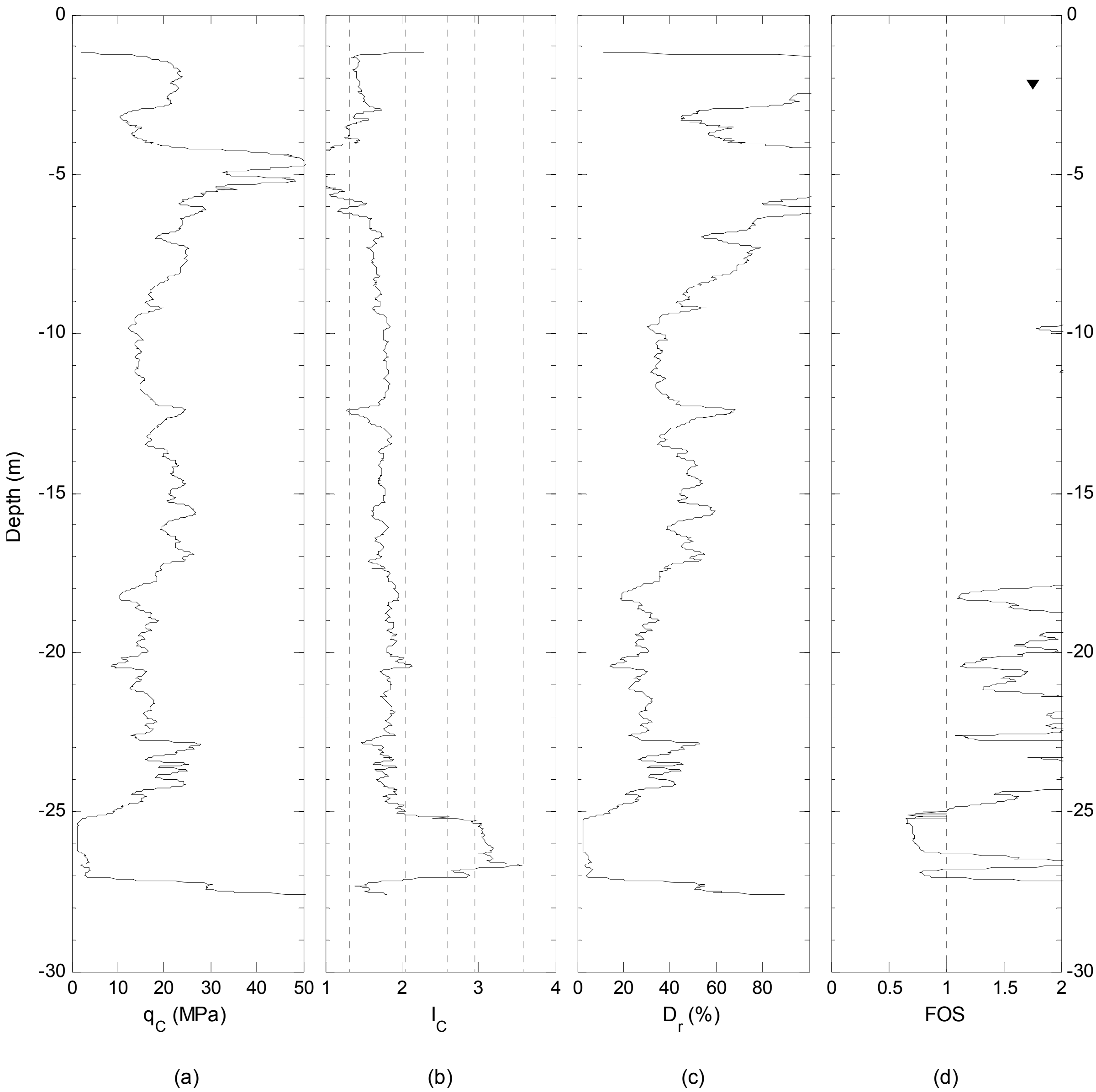


Figure 44 Summary of CPT liquefaction triggering calculations of the SHLC SMS for the Darfield earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

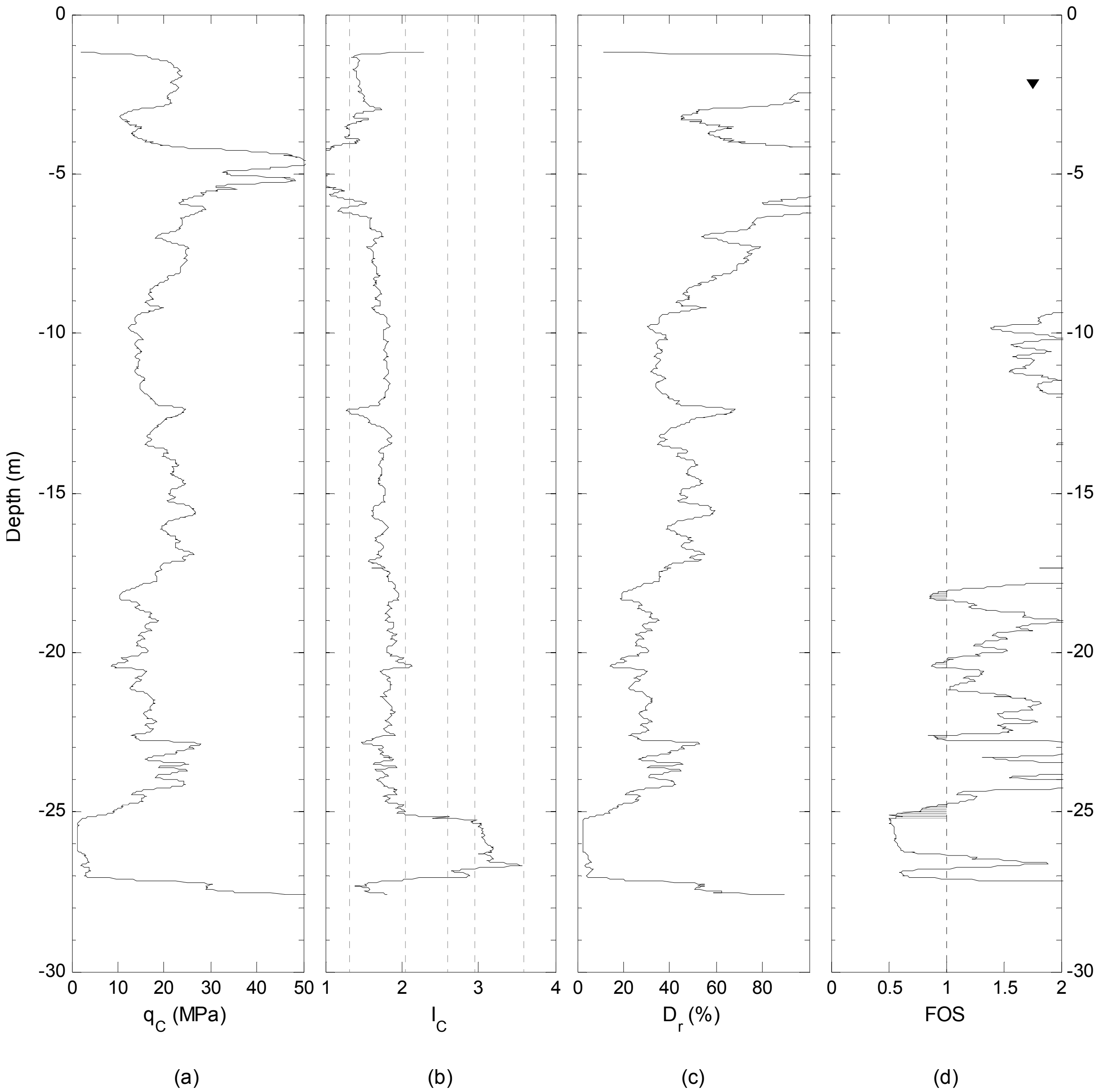


Figure 45 Summary of CPT liquefaction triggering calculations of the SHLC SMS for the Christchurch earthquake (a) CPT tip resistance, (b) soil behaviour type index, (c) relative density, (d) factor of safety

Appendix C SMS Site Investigation Data

This Appendix provides a complete collation of all the raw site investigation data in the vicinity of each SMS. At locations with site investigations in the surrounding area, and additional set of site investigation data for this region is presented.

C.1 Christchurch Aero Club (CACS)

Nearby Geotechnical Site Investigation

Table 9 CACS geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	0	Gravel site
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	
H/V (HV)	1	

Figure 46 CACS geotechnical site investigation location plan

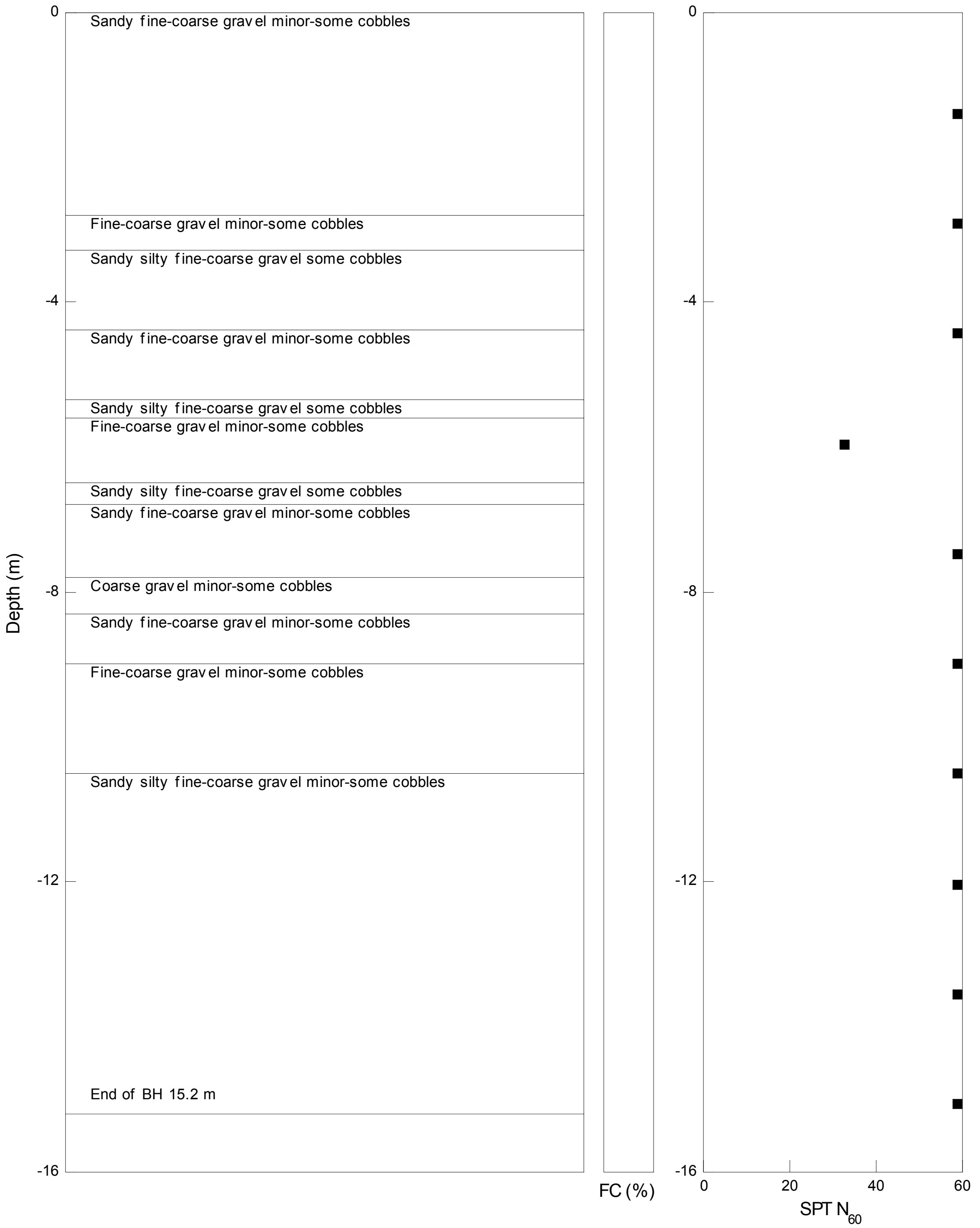
Borehole (CACS_BH1)

Latitude Longitude (WGS 84): -43.482961 172.529478

Drilling method : Sonic core

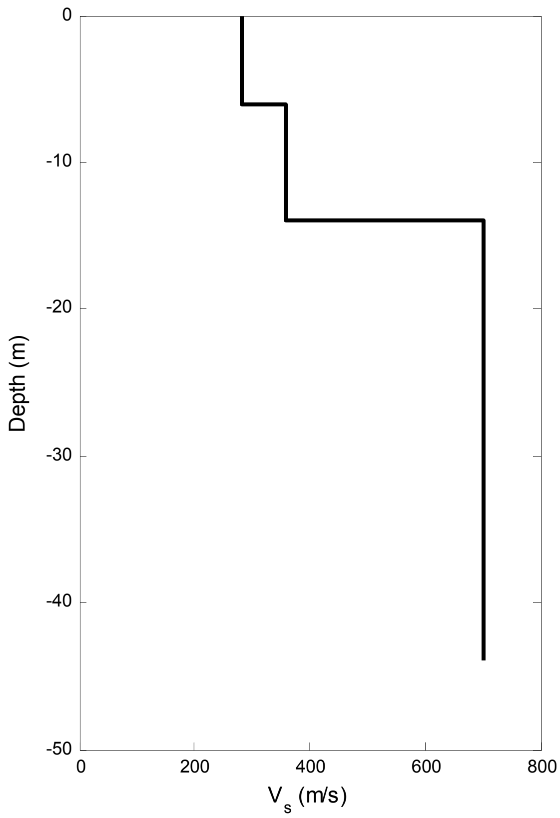
Water table depth: not encountered

Depth: 15.2 m



Shear Wave Profile (CACS_SW1)

Latitude Longitude (WGS 84):	-43.483112 172.529655
Method:	Active source (MASW, SASW) - Linear array of 24 4.5 Hz vertical geophones @ 2 m spacing
Source offsets:	5 m, 10m, 20m
Source:	10 sledgehammer impacts per offset
Depth:	44 m



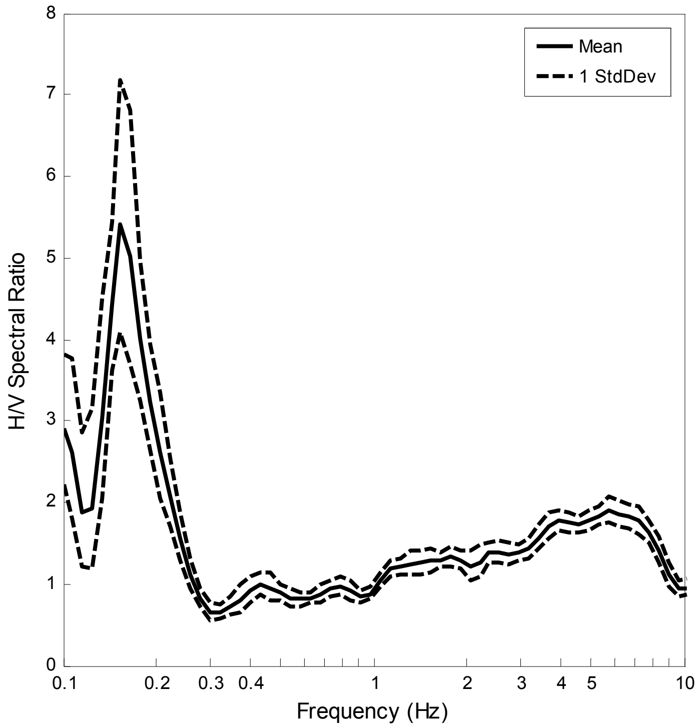
Depth (m)	V_S (m/s)
0.0	282
6.0	360
14.0	700
44.0	

Horizontal-to-vertical (H/V) spectral ratio (CACS_HV1)

Latitude Longitude (WGS 84): -43.483082 172.529829

Equipment: Nanometrics Trillium compact 120 second broadband seismometer

Record length: 1 hour



C.2 Christchurch Botanical Gardens (CBGS)

Nearby Geotechnical Site Investigation

Table 10 CBGS geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	Predrilled through surface gravel
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

Figure 47 CBGS geotechnical site investigation location plan

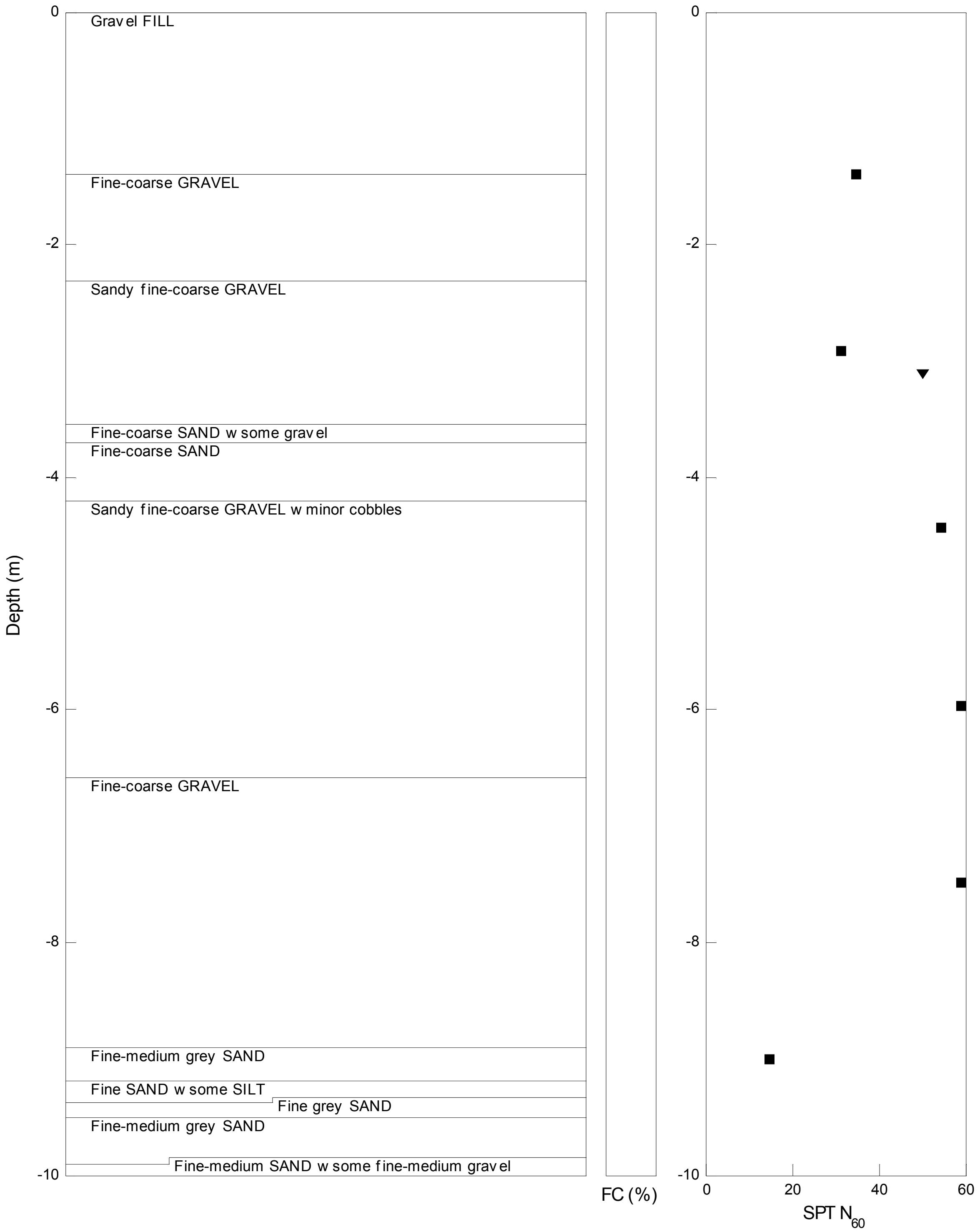
Borehole (CBGS_BH1)

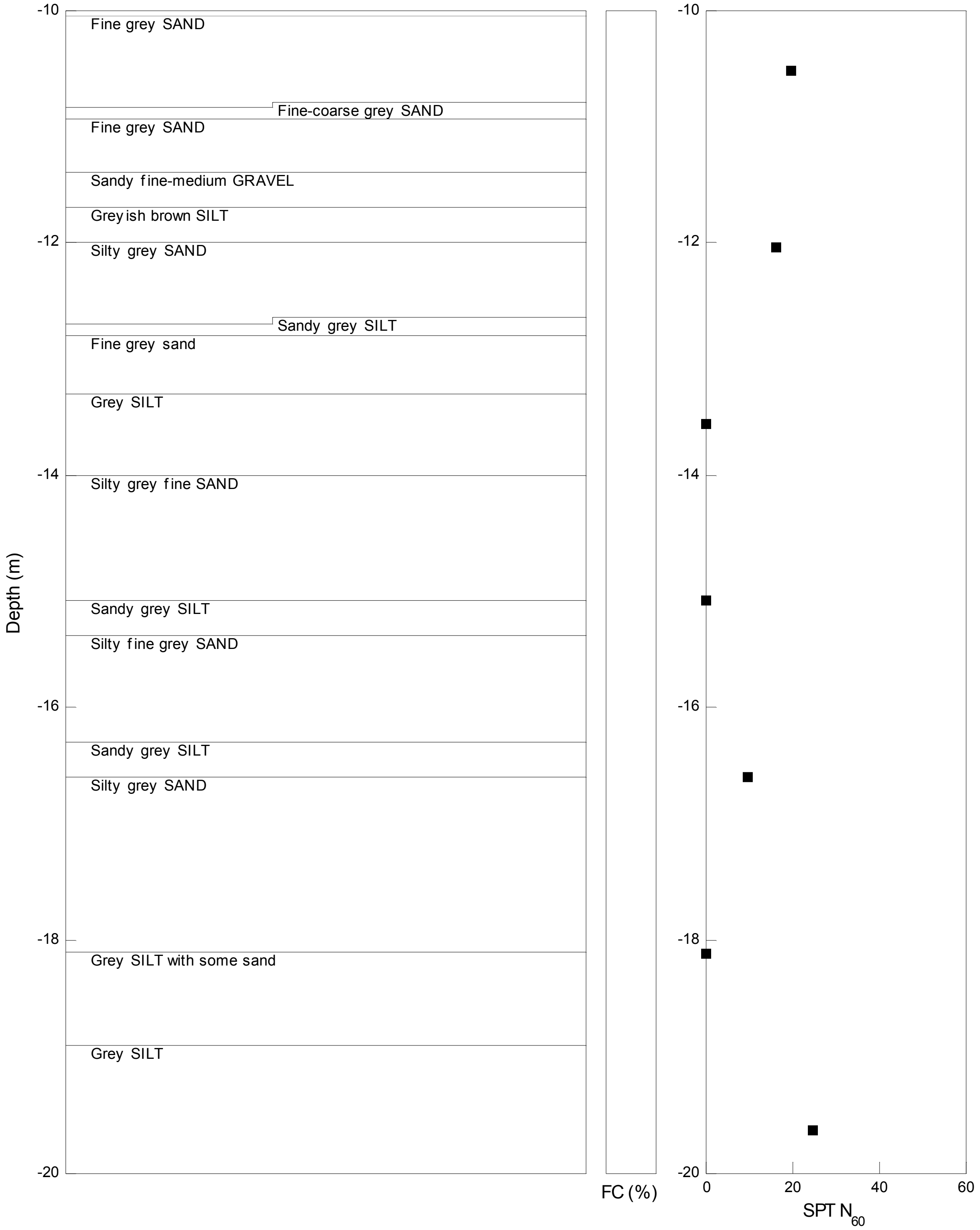
Latitude Longitude (WGS 84): -43.529358 172.619876

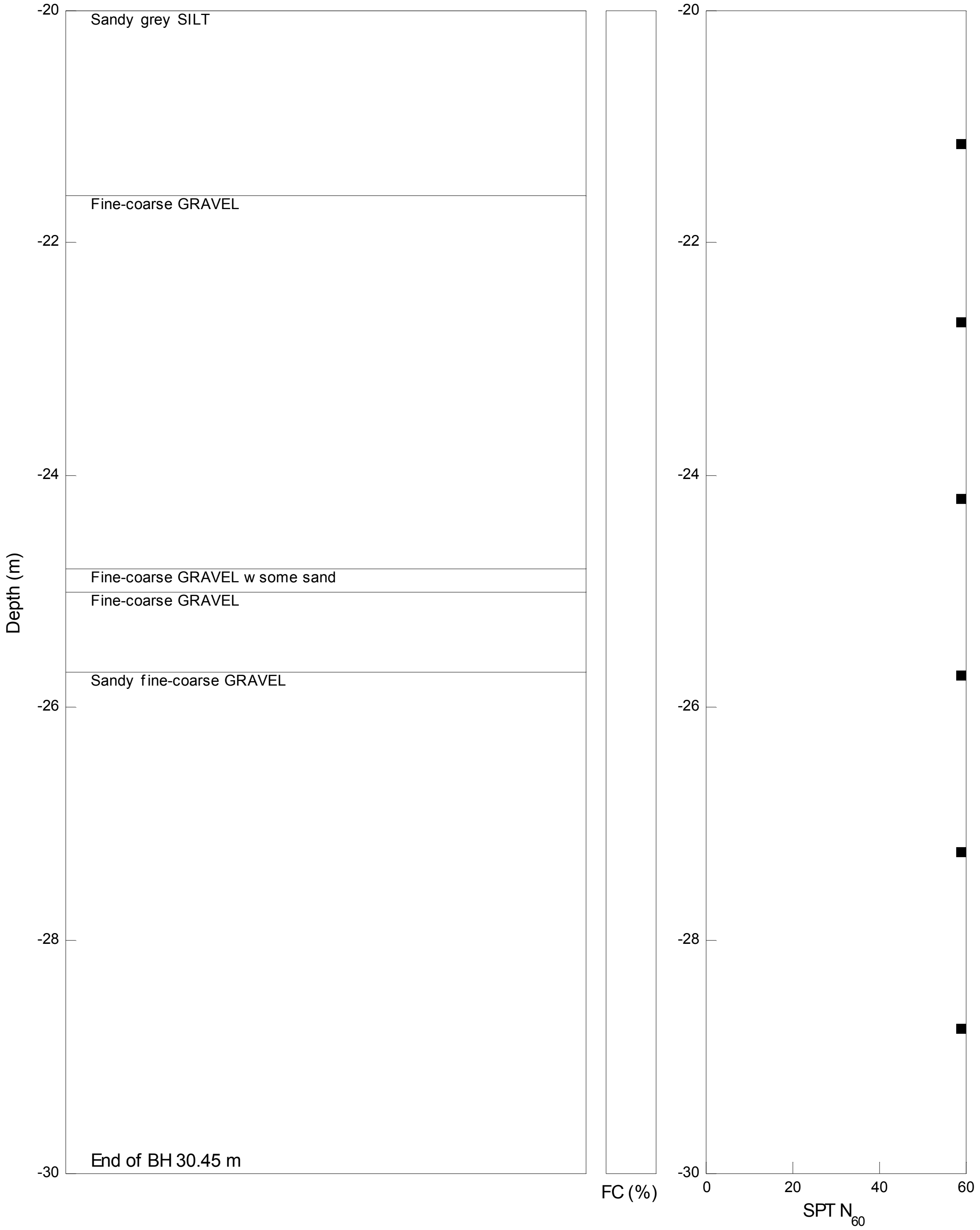
Drilling method : Sonic core

Water table depth: 3.2 m

Depth: 30.45 m




Depth (m)
-10
-12
-14
-16
-18
-20
Fine grey SAND
Fine-coarse grey SAND
Fine grey SAND
Sandy fine-medium GRAVEL
Greyish brown SILT
Silty grey SAND
Sandy grey SILT
Fine grey sand
Grey SILT
Silty grey fine SAND
Sandy grey SILT
Silty fine grey SAND
Sandy grey SILT
Silty grey SAND
Grey SILT with some sand
Grey SILT
FC (%)
0
20
40
60
SPT N60



Depth (m)
-20
-22
-24
-26
-28
-30
Sandy grey SILT
Fine-coarse GRAVEL
Fine-coarse GRAVEL w some sand
Fine-coarse GRAVEL
Sandy fine-coarse GRAVEL
End of BH 30.45 m
FC (%)
0
20
40
60
SPT N_{60}

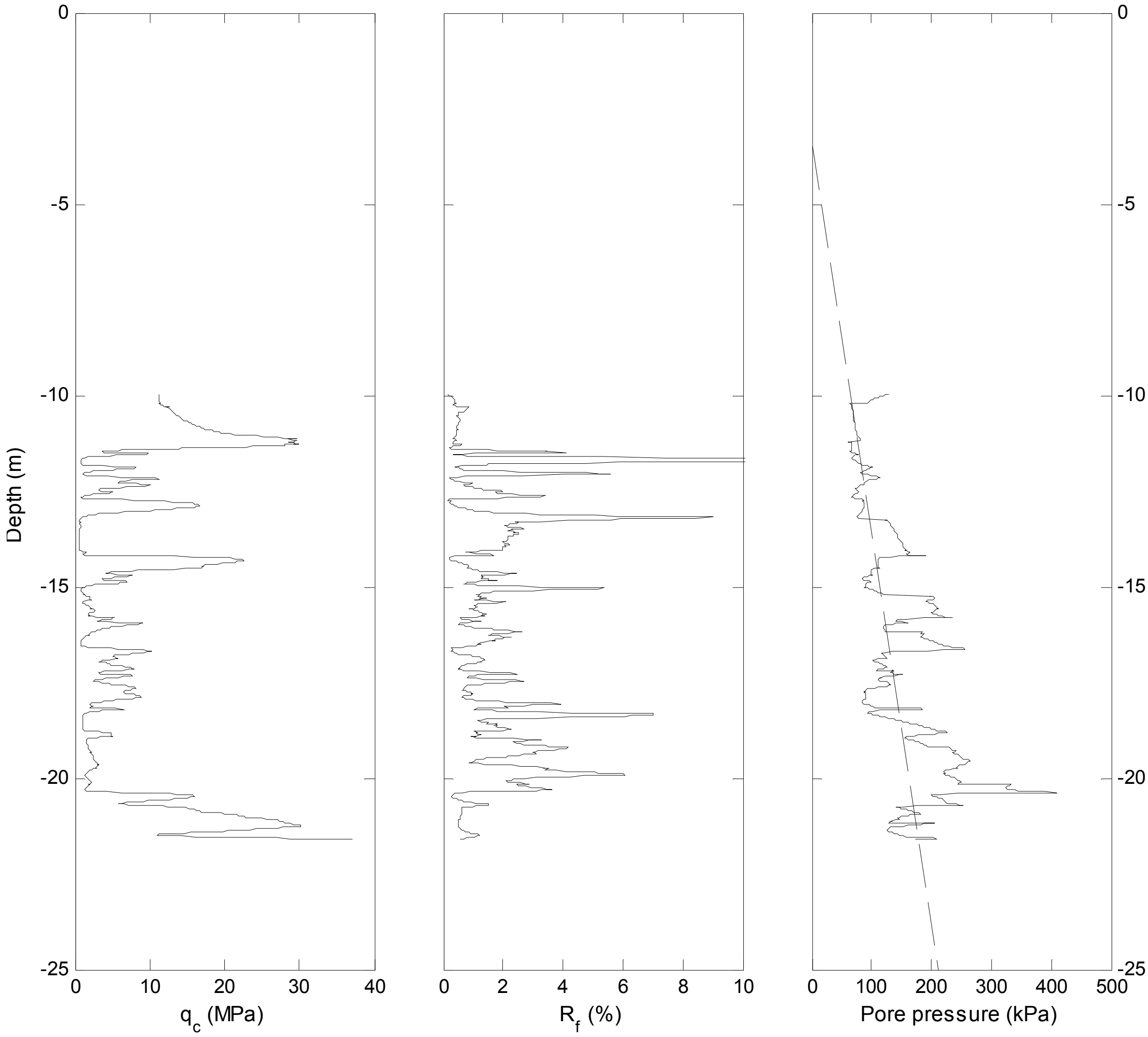
Cone Penetrometer (CBGS_CPT1)

Latitude Longitude (WGS 84): -43.529356 172.619870

Water table depth: 3.2 m

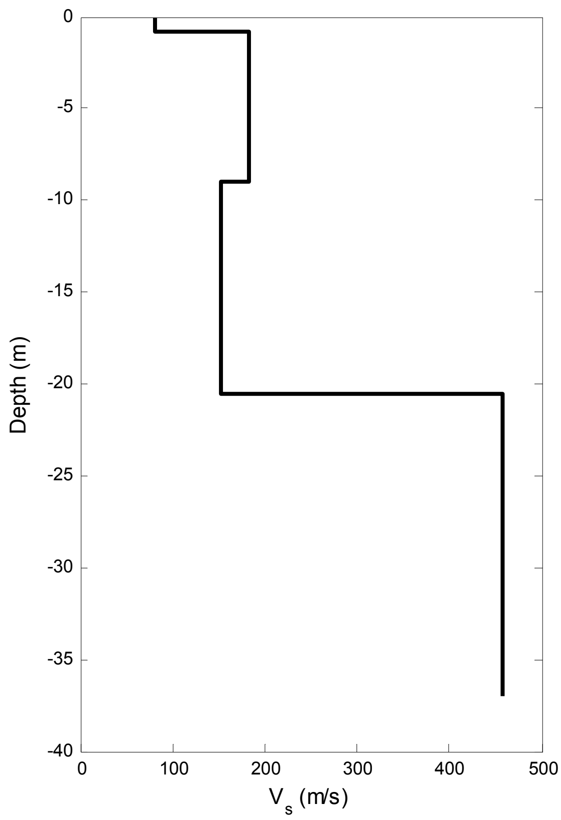
Predrilled: 9.88 m

Depth: 21.6 m



Shear Wave Profile (CBGS_SW1)

Latitude Longitude (WGS 84):	-43.529219 172.619752
Methods:	Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing. Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.
Source offsets:	4.6 m, 9.1m, 18.3 m
Source:	Minimum of five sledgehammer impacts per offset
Depth:	37 m



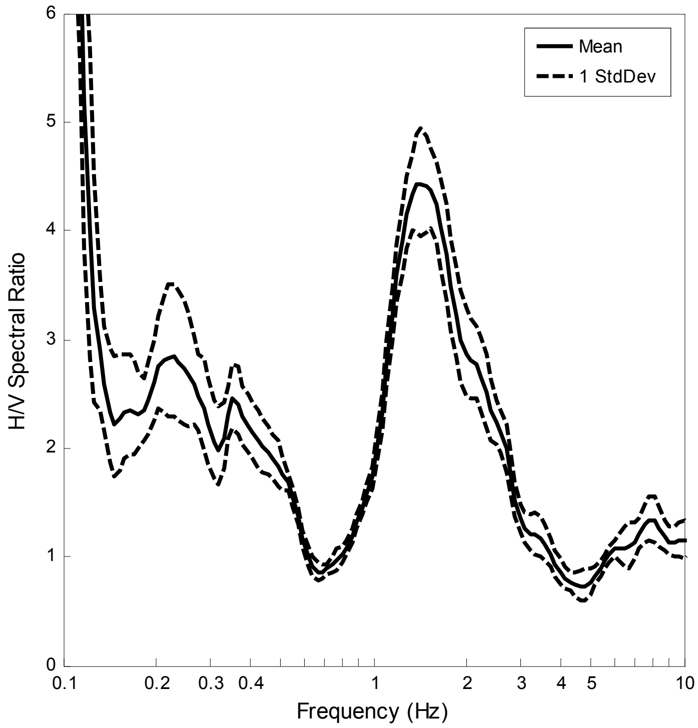
Depth (m)	V_S (m/s)
0.0	81
0.85	183
9.0	152
20.5	457
37.0	

Horizontal-to-vertical (H/V) spectral ratio (CBGS_HV1)

Latitude Longitude (WGS 84): -43.529372 172.619856

Equipment: Nanometrics Trillium compact 120 second broadband seismometer

Record length: 1 hour



C.3 Christchurch Cathedral College (CCCC)

Nearby Geotechnical Site Investigation

Table 11 CCCC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

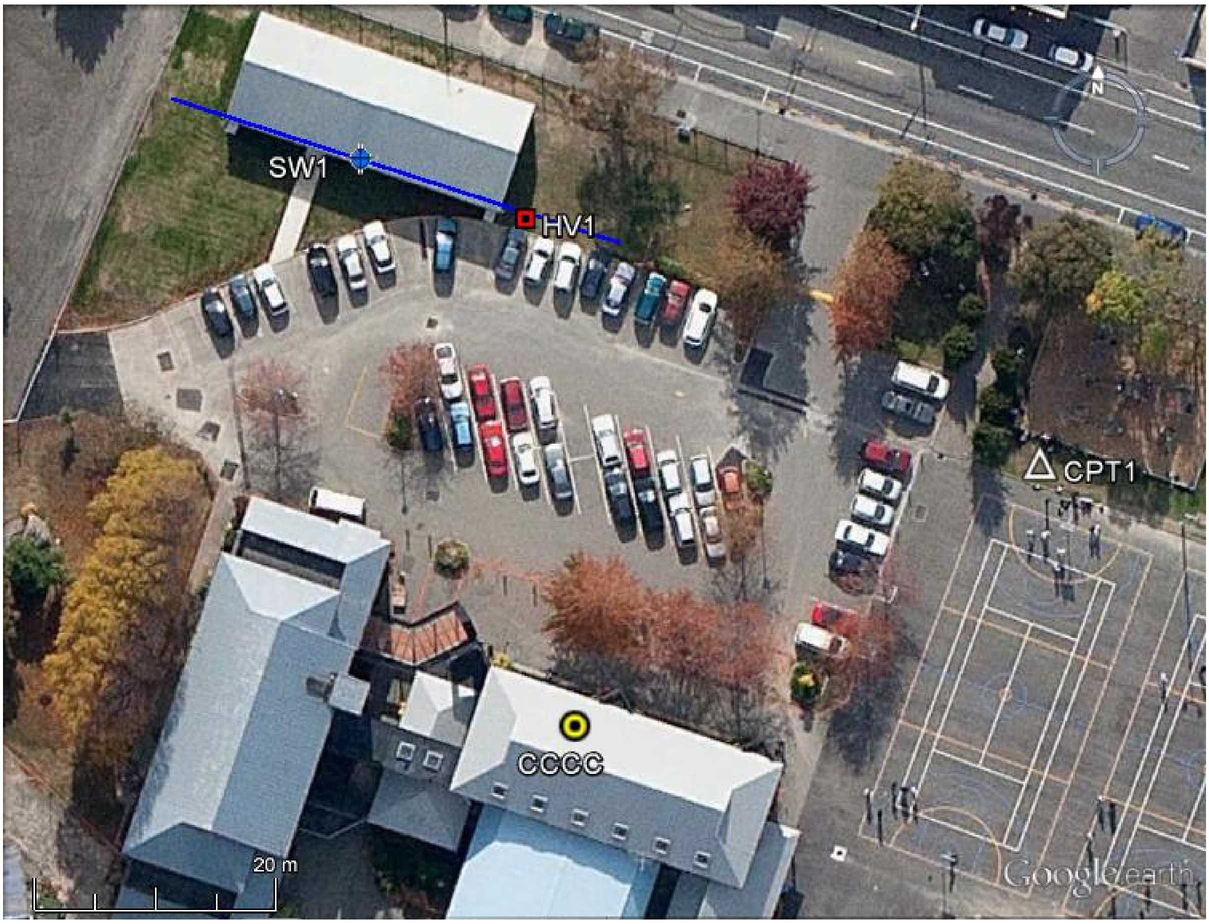
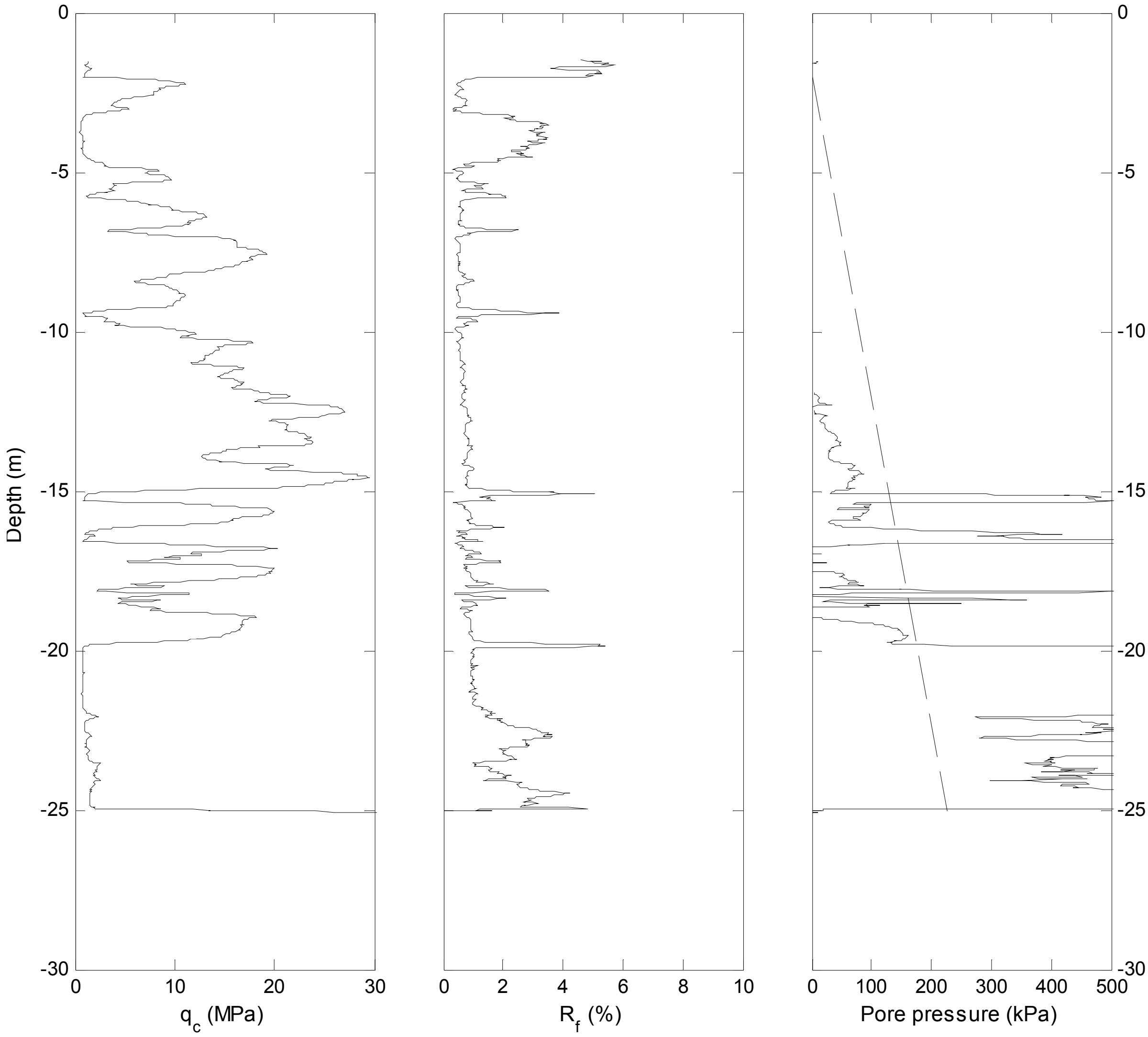


Figure 48 CCCC geotechnical site investigation location plan

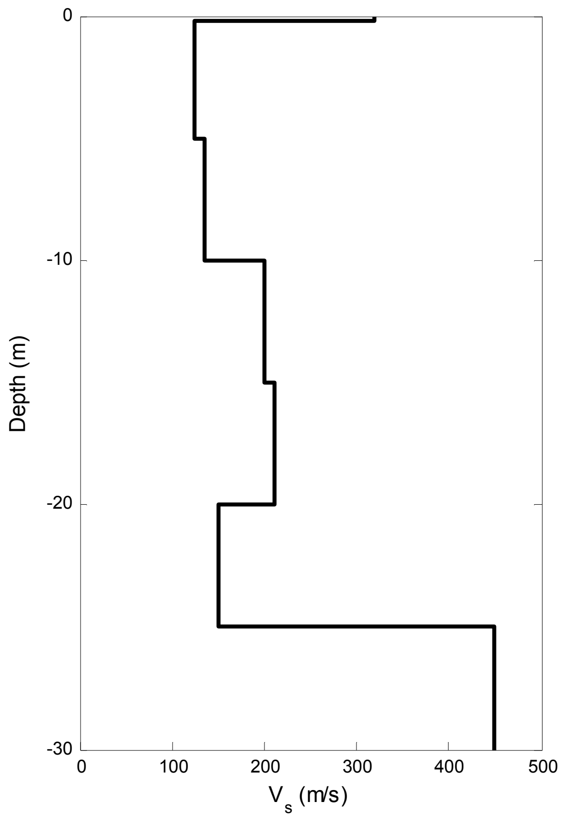
Cone Penetrometer (CCCC_CPT1)

Latitude Longitude (WGS 84):	-43.537879 172.647910
Water table depth:	2 m
Predrilled:	1.5 m
Depth:	25.11 m



Shear Wave Profile (CCCC_SW1)

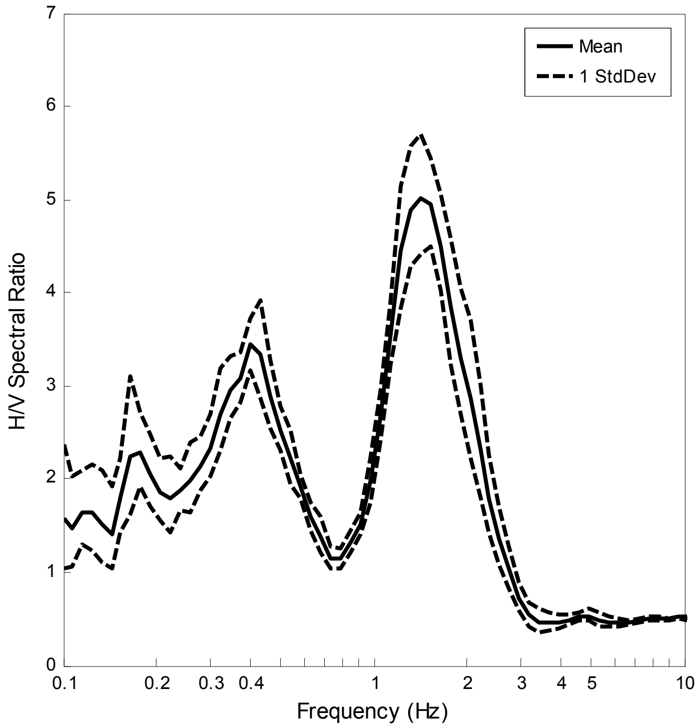
Latitude Longitude (WGS 84):	-43.537650 172.647200
Methods:	Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing. Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.
MASW Source offsets:	4.6 m, 9.1m, 18.3 m
Source:	Minimum of five sledgehammer impacts per offset
Depth:	30 m



Depth (m)	V_S (m/s)
0.0	320
0.21	125
5.0	135
11.0	210
15.0	240
20.0	170
25.0	470
30.0	

Horizontal-to-vertical (H/V) spectral ratio (CCCC_HV1)

Latitude Longitude (WGS 84):	-43.537694 172.647373
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



Surrounding Geotechnical Site Investigation

Table 12 CCCC surrounding geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	3	
Borehole/SPT (BH)	2	
V_s – surface wave (SW)	0	
H/V Spectral Ratio (HV)	0	

Figure 49 CCCC surrounding geotechnical site investigation location plan

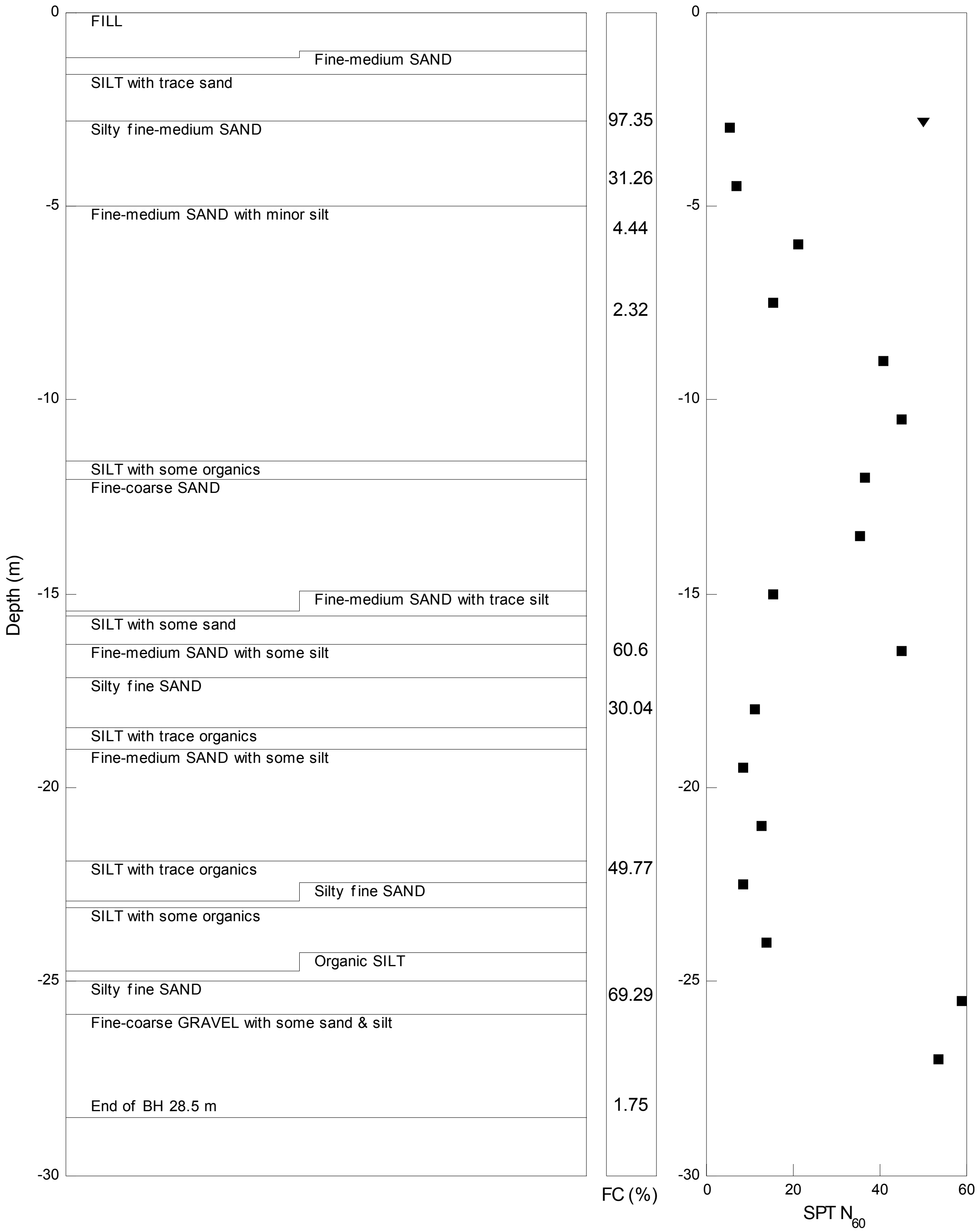
Borehole (CCCC_BHS1)

Latitude Longitude (WGS 84): -43.536070 172.650320

Drilling method : Sonic

Water table depth: 2.9 m

Depth: 28.5 m



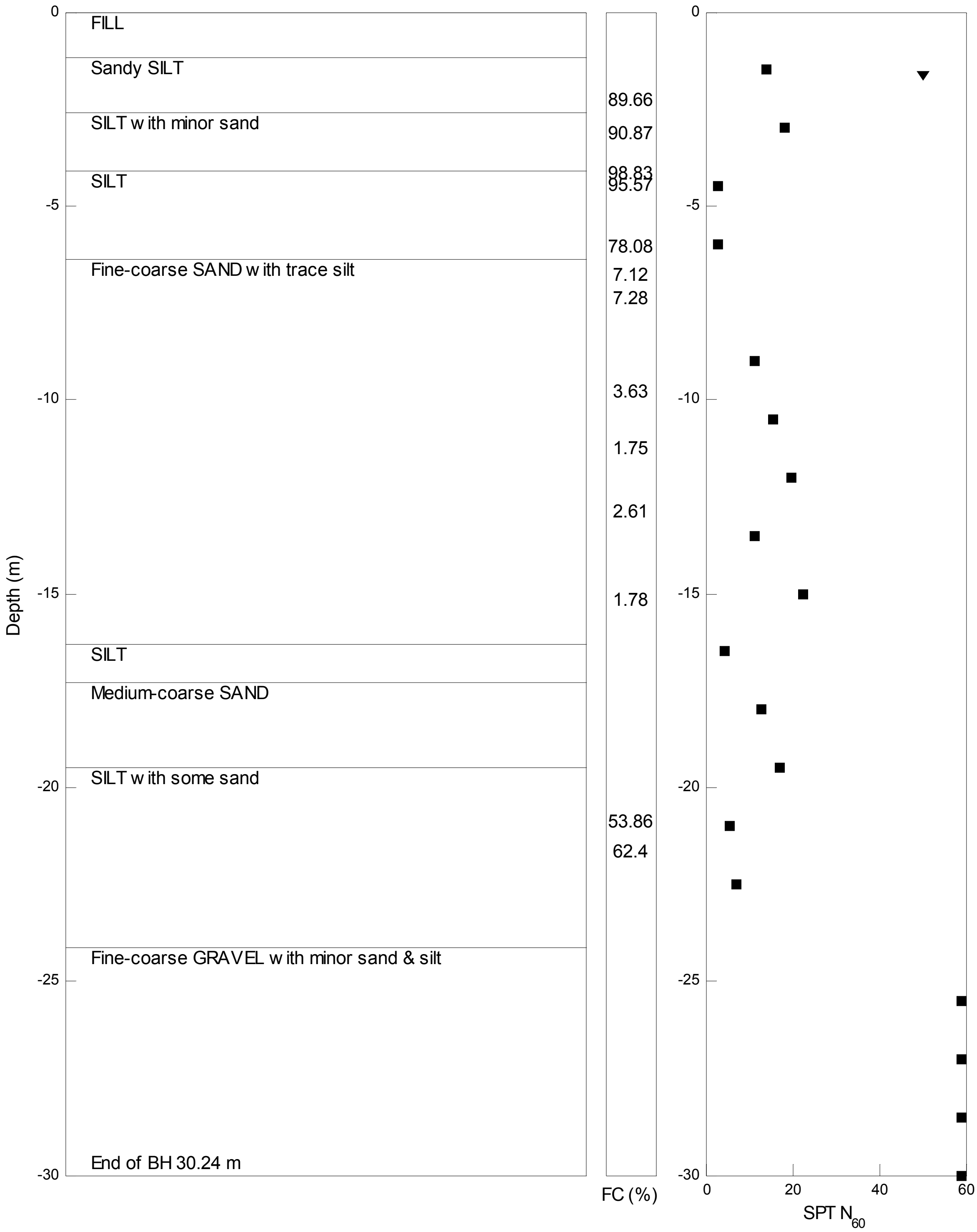
Borehole (CCCC_BHS2)

Latitude Longitude (WGS 84): -43.536531 172.645499

Drilling method : Sonic

Water table depth: 1.7 m

Depth: 30.24 m



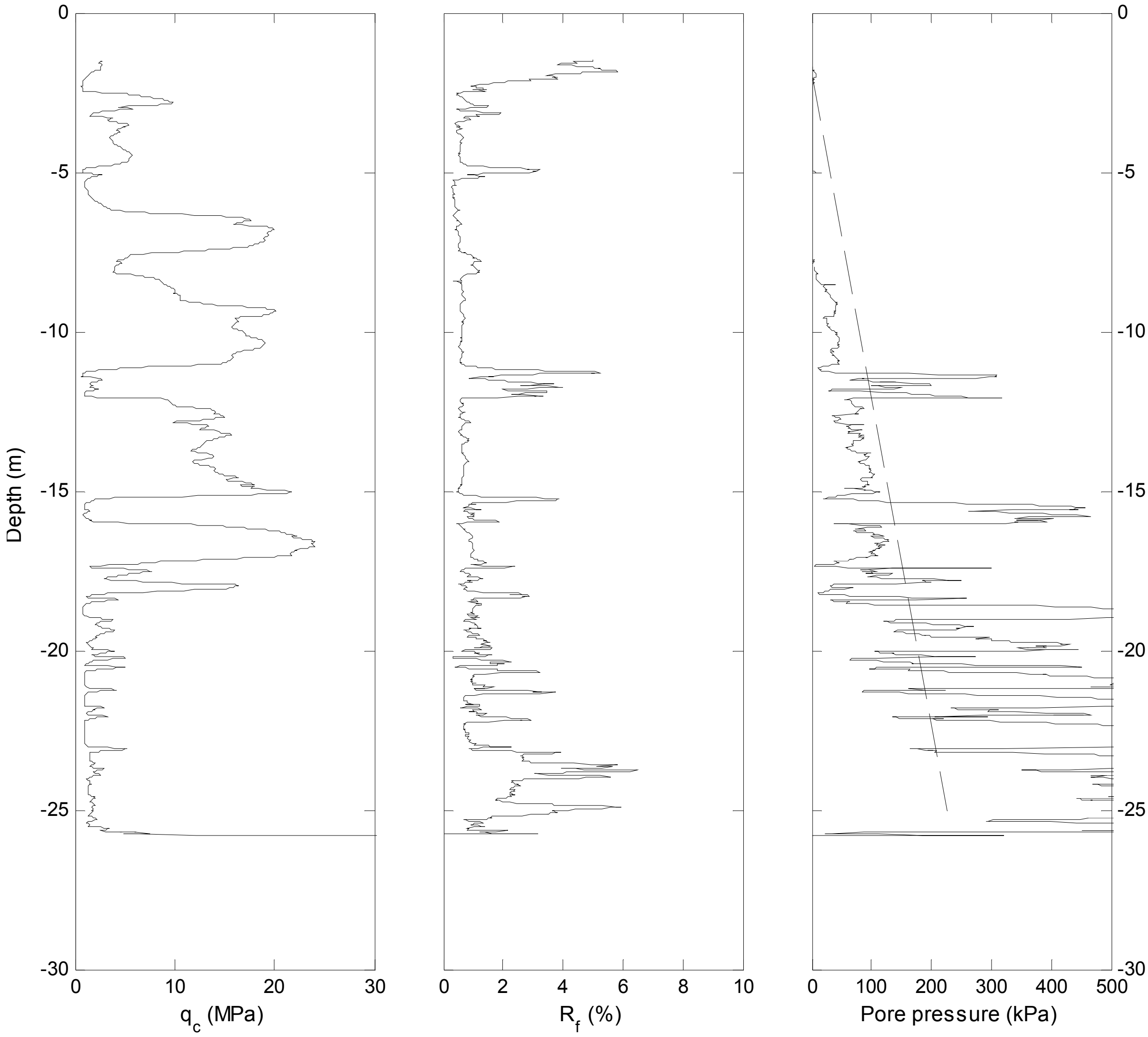
Cone Penetrometer (CCCC_CPTS1)

Latitude Longitude (WGS 84): -43.536201 172.650294

Water table depth: 2 m

Predrilled: 1.5 m

Depth: 25.82 m



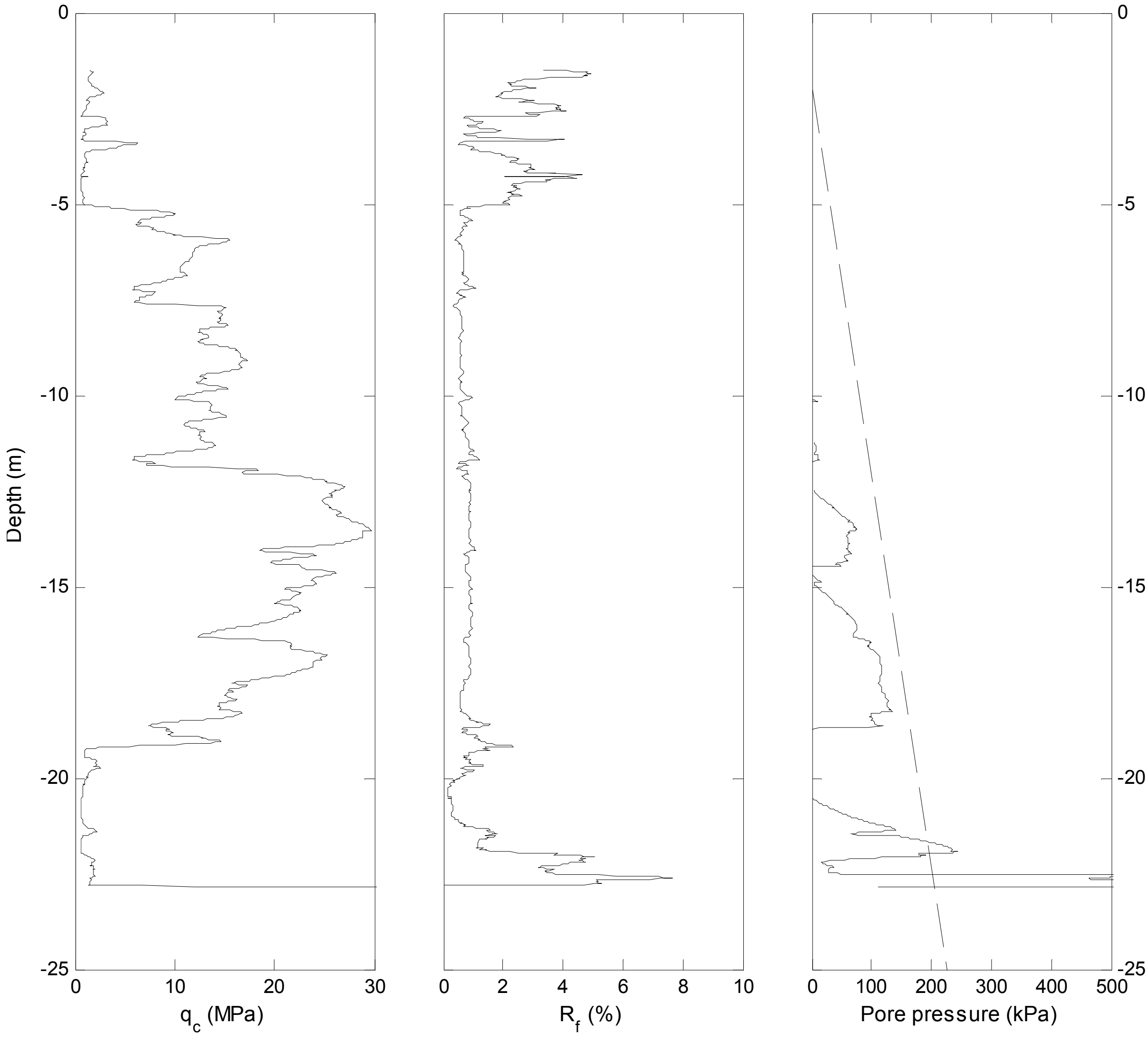
Cone Penetrometer (CCCC_CPTS2)

Latitude Longitude (WGS 84): -43.538356 172.645501

Water table depth: 2 m

Predrilled: 1.5 m

Depth: 22.87 m



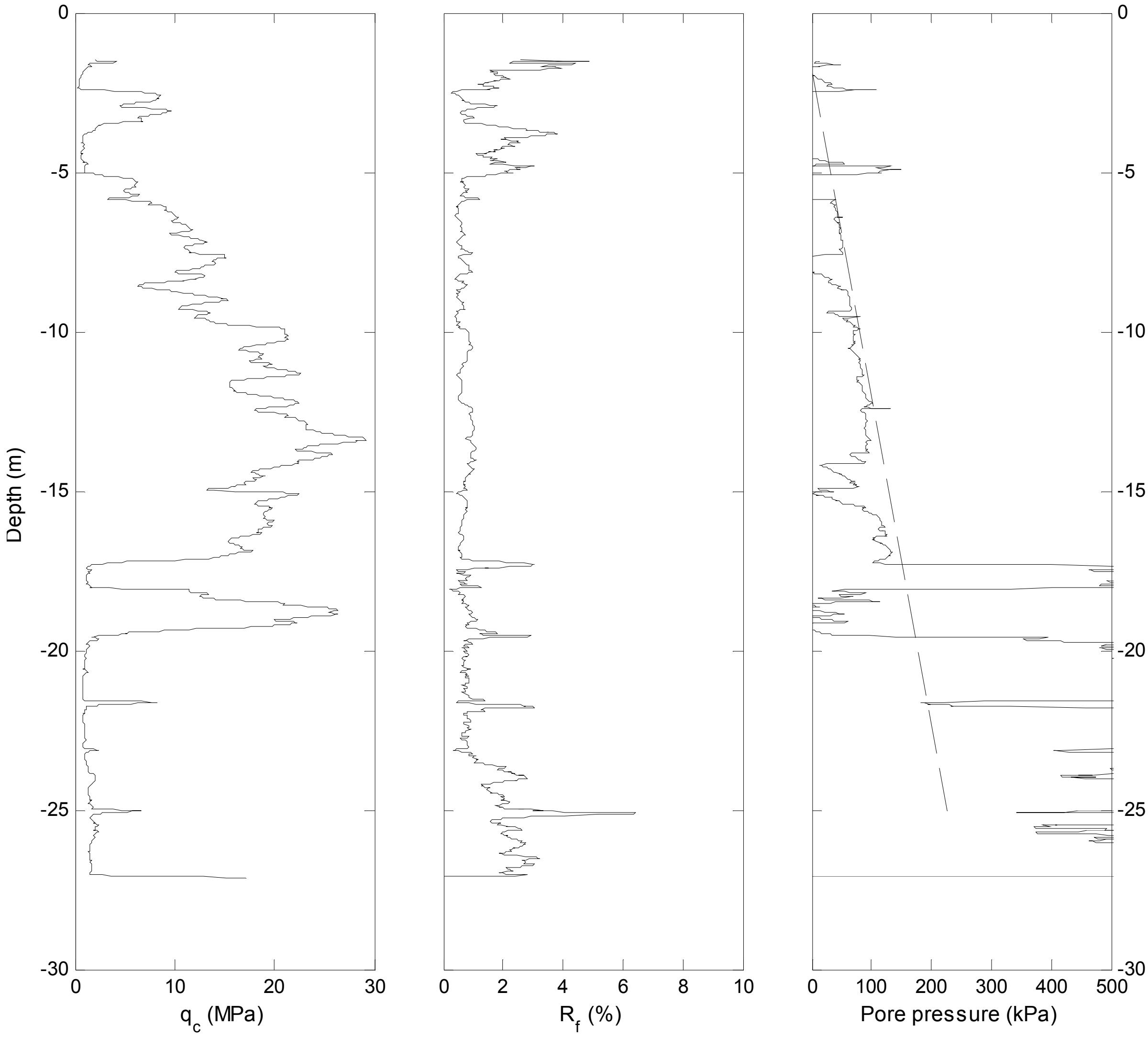
Cone Penetrometer (CCCC_CPTS3)

Latitude Longitude (WGS 84): -43.538498 172.650291

Water table depth: 1.9 m

Predrilled: 1.5 m

Depth: 27.13 m



C.4 Christchurch Hospital (CHHC)

Nearby Geotechnical Site Investigations

Table 13 CHHC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	2	
Borehole/SPT (BH)	2	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

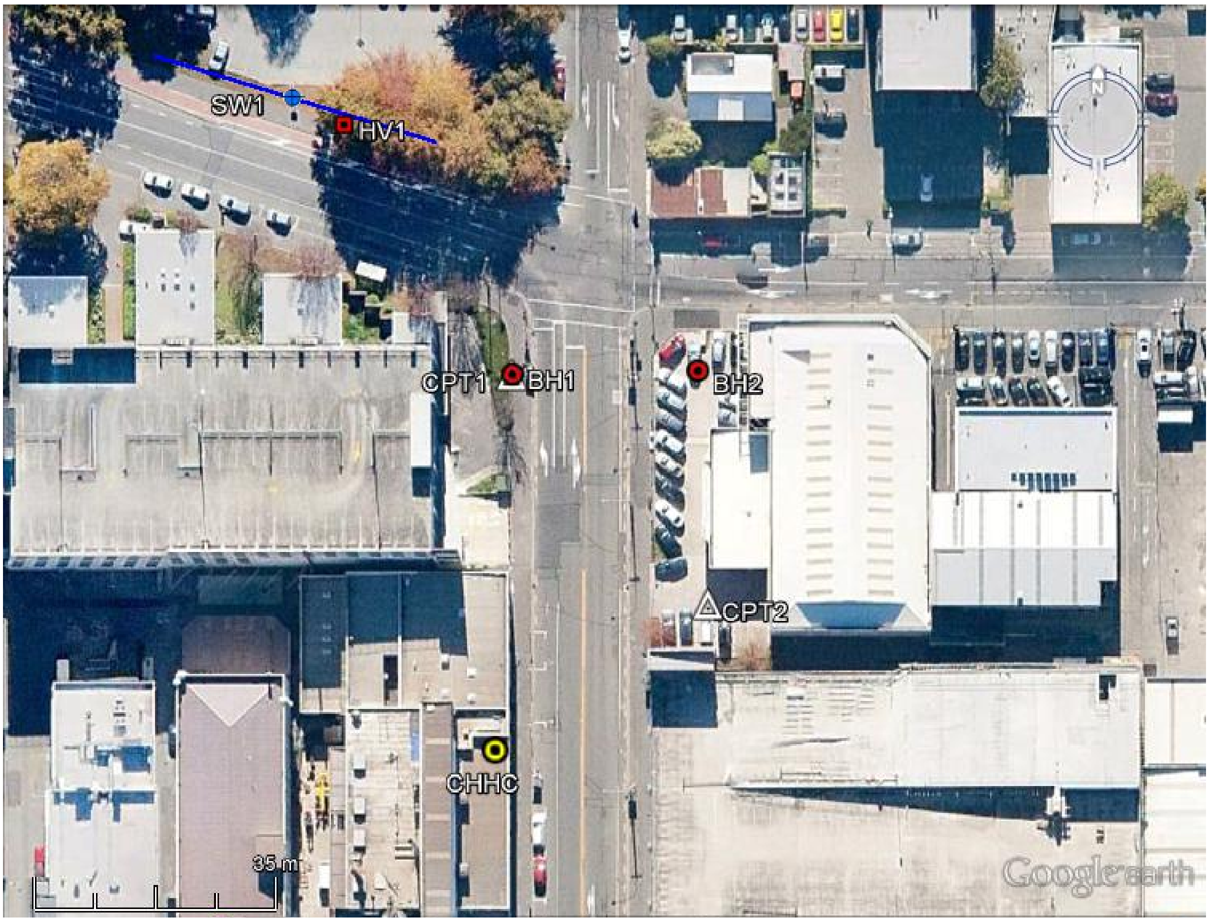


Figure 50 CHHC geotechnical site investigation location plan

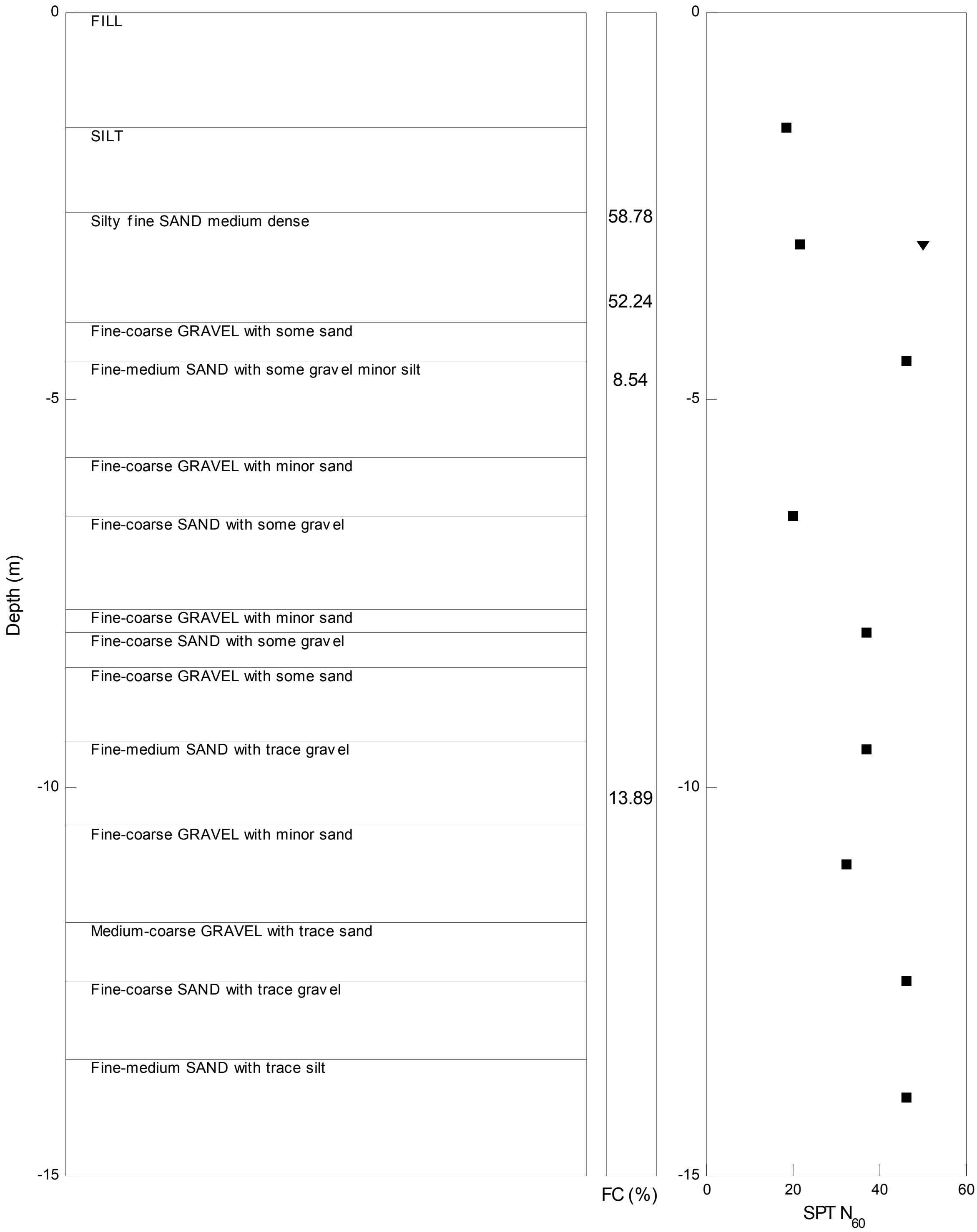
Borehole (CHHC_BH1)

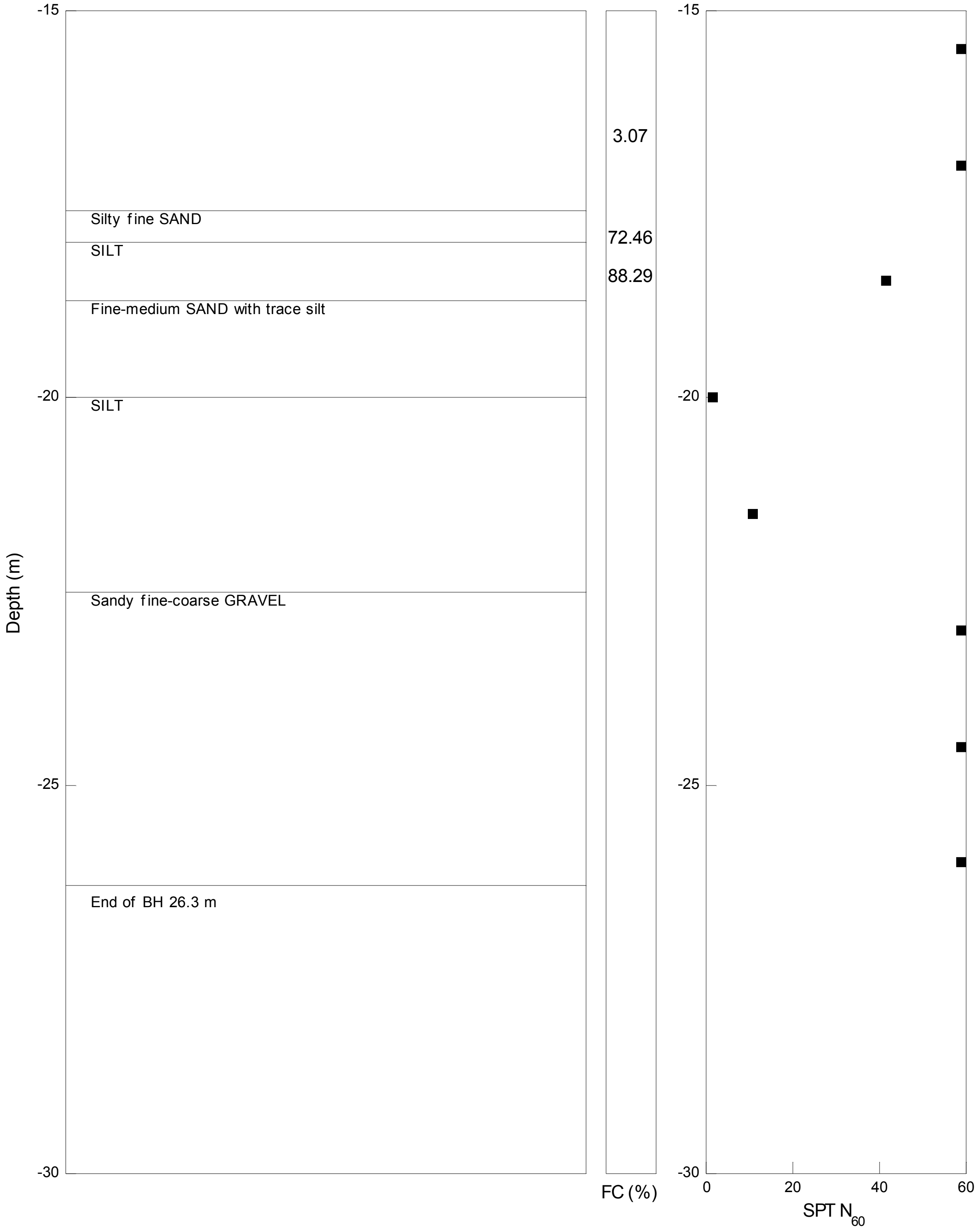
Latitude Longitude (WGS 84): -43.535438 172.627464

Drilling method : Rotary Mud

Water table depth: 3.1 m

Depth: 26.29 m




Depth (m)
-15
-20
-25
-30
Silty fine SAND
SILT
Fine-medium SAND with trace silt
SILT
Sandy fine-coarse GRAVEL
End of BH 26.3 m
3.07
72.46
88.29
FC (%)
0
20
40
60
SPT N60

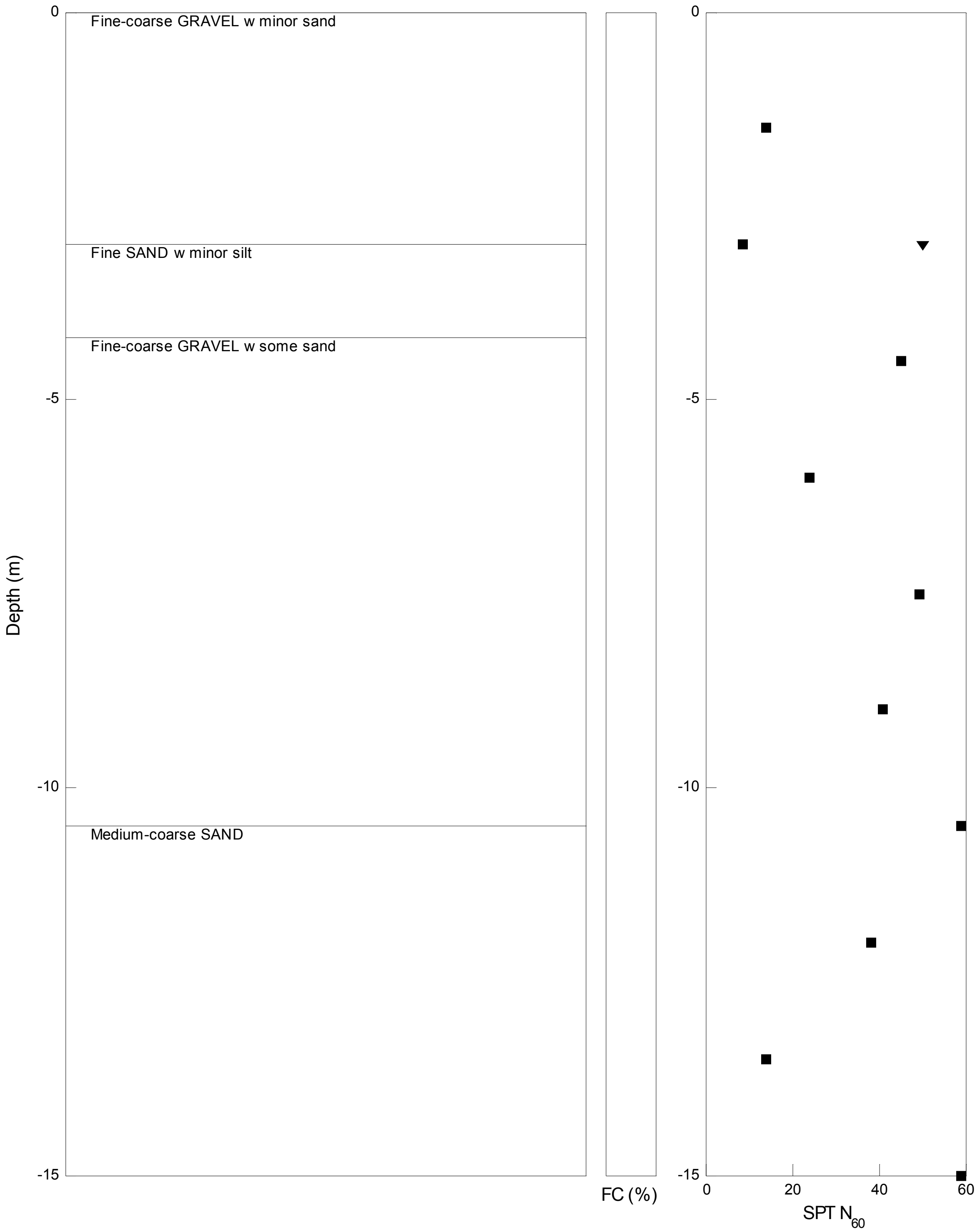
Borehole (CHHC_BH2)

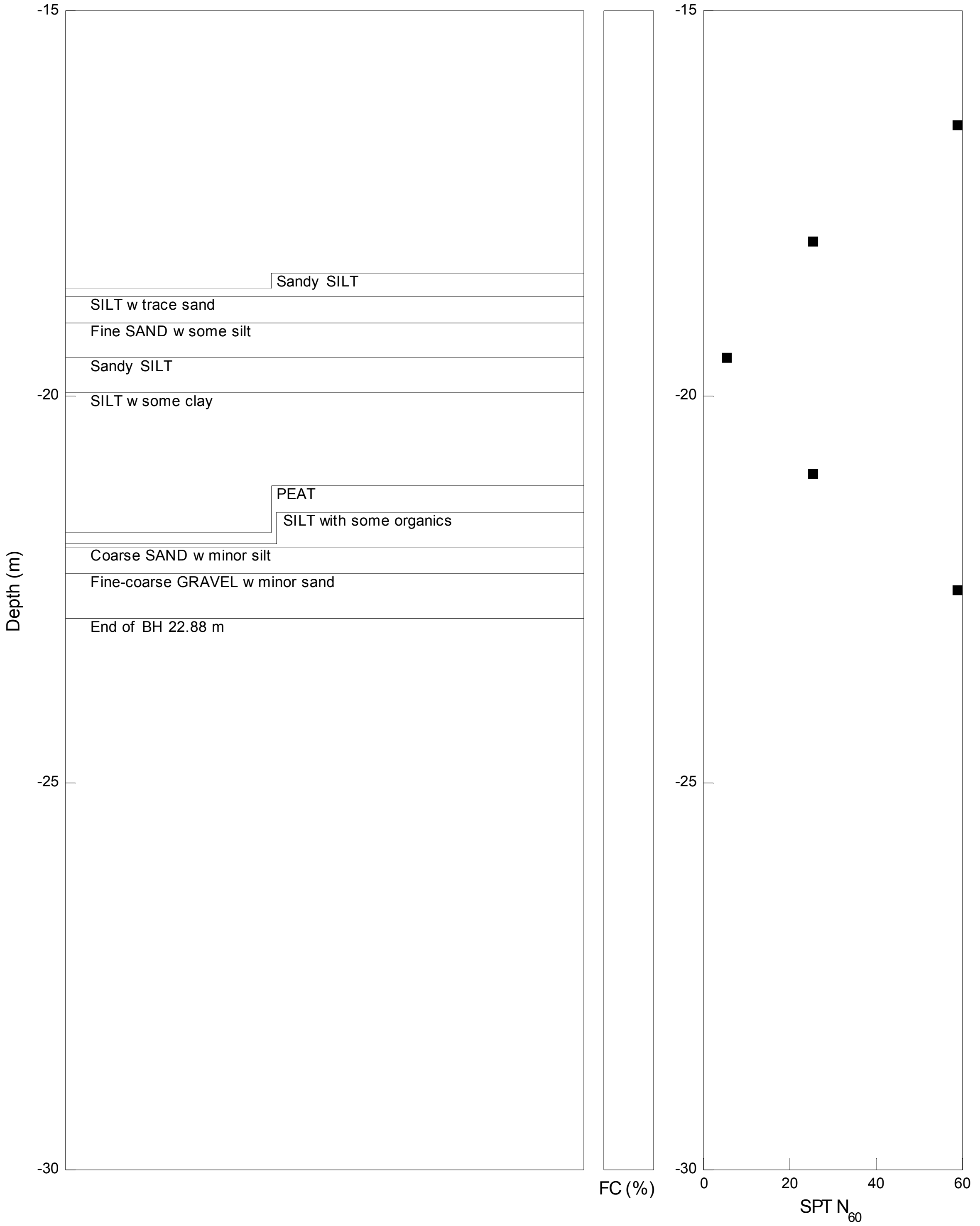
Latitude Longitude (WGS 84): -43.535433 172.627797

Drilling method : Sonic

Water table depth: 3.0 m

Depth: 22.88 m




Depth (m)
-15
-20
-25
-30
Sandy SILT
SILT w trace sand
Fine SAND w some silt
Sandy SILT
SILT w some clay
PEAT
SILT with some organics
Coarse SAND w minor silt
Fine-coarse GRAVEL w minor sand
End of BH 22.88 m
FC (%)
0
20
40
60
SPT N60

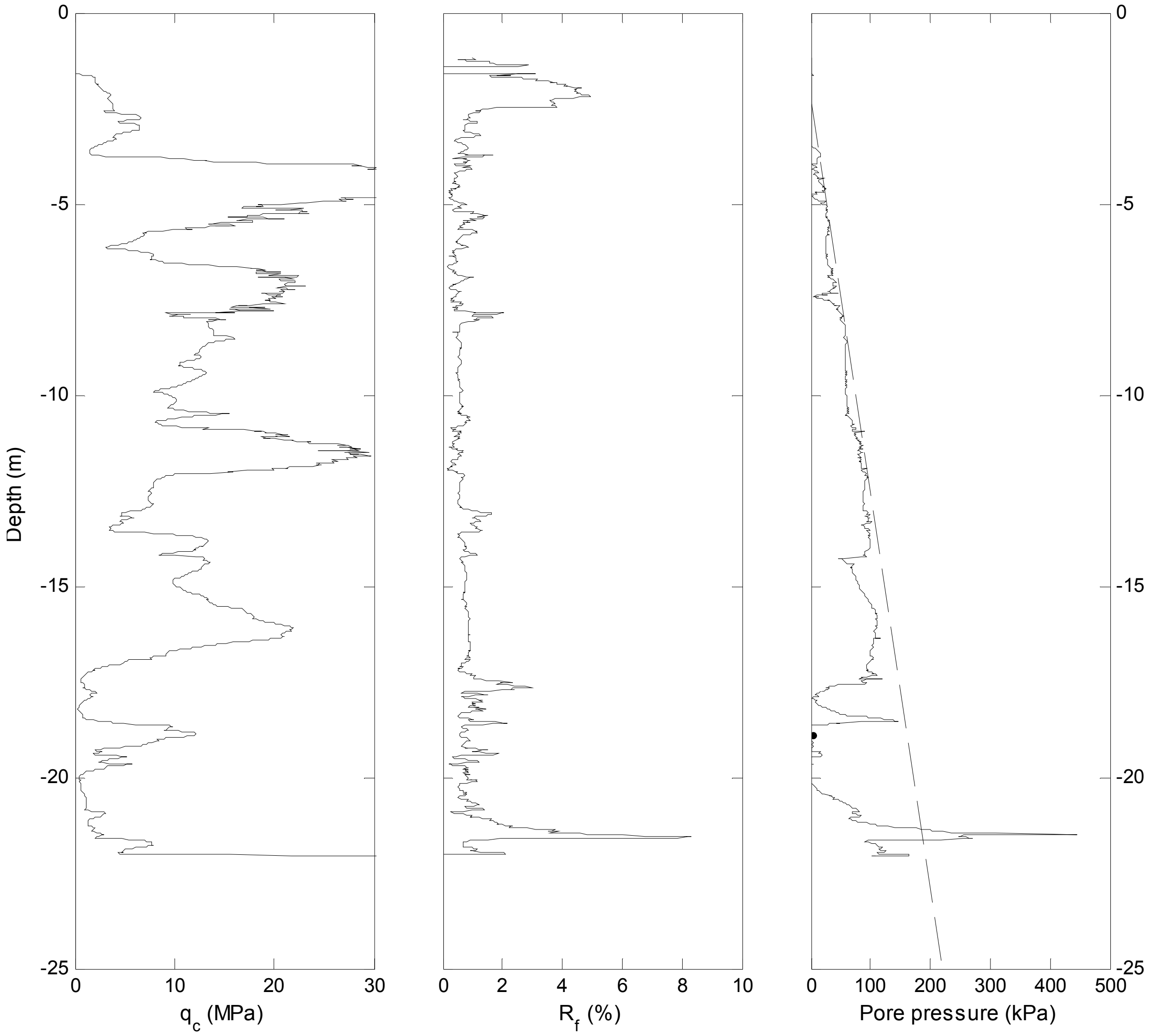
Cone Penetrometer (CHHC_CPT1)

Latitude Longitude (WGS 84): -43.535441 172.627461

Water table depth: 2.4 m

Predrilled: 1.2 m

Depth: 22.08 m



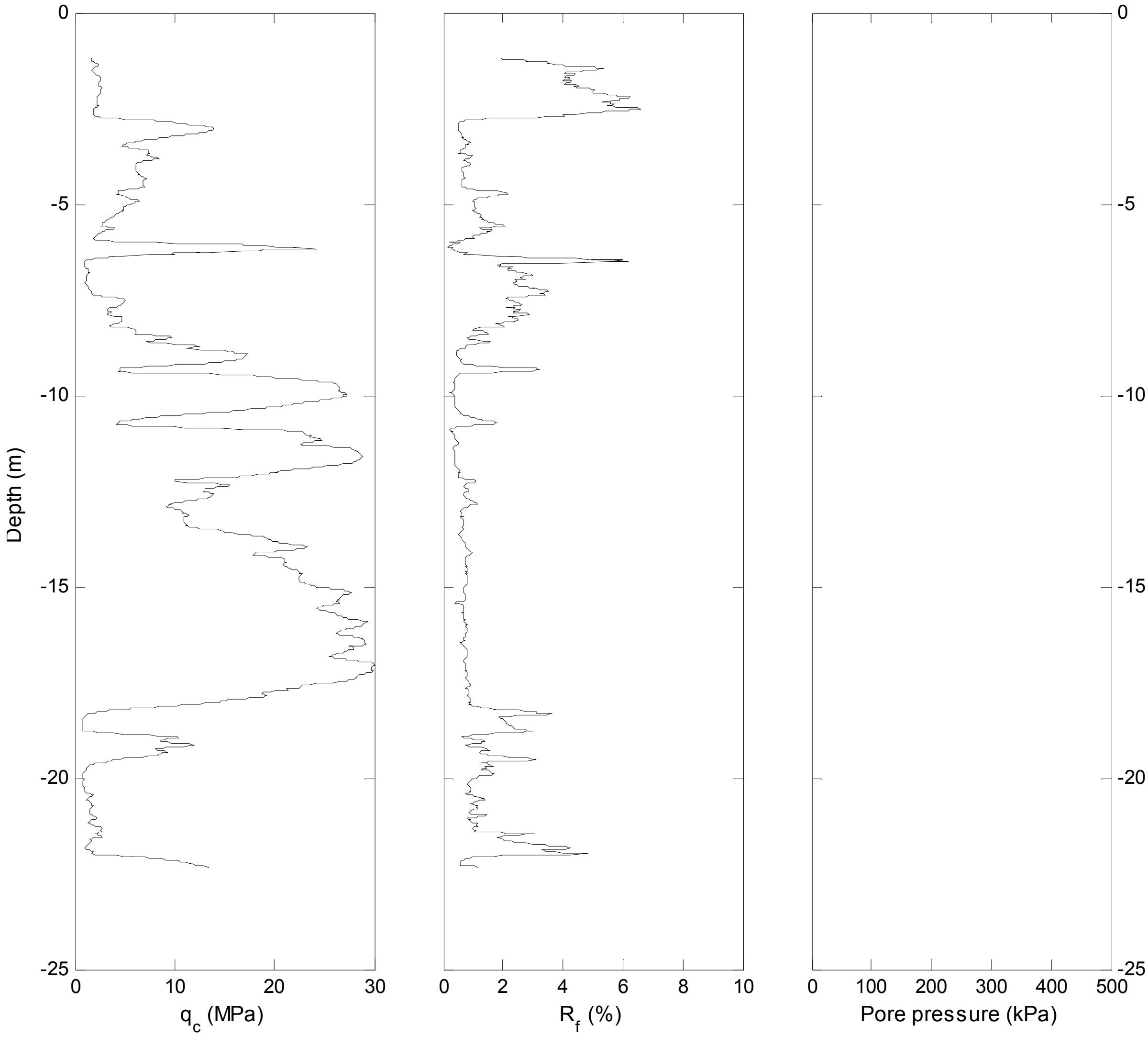
Cone Penetrometer (CHHC_CPT2)

Latitude Longitude (WGS 84): -43.535739 172.627814

Water table depth: -

Predrilled: 0.25 m

Depth: 22.32 m



Shear Wave Profile (CHHC_SW1)

Latitude Longitude (WGS 84): -43.535133 172.627050

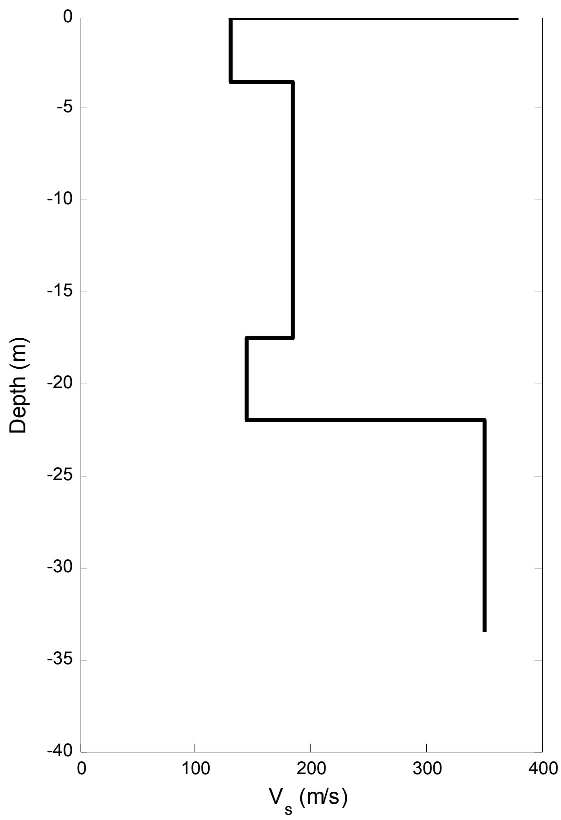
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

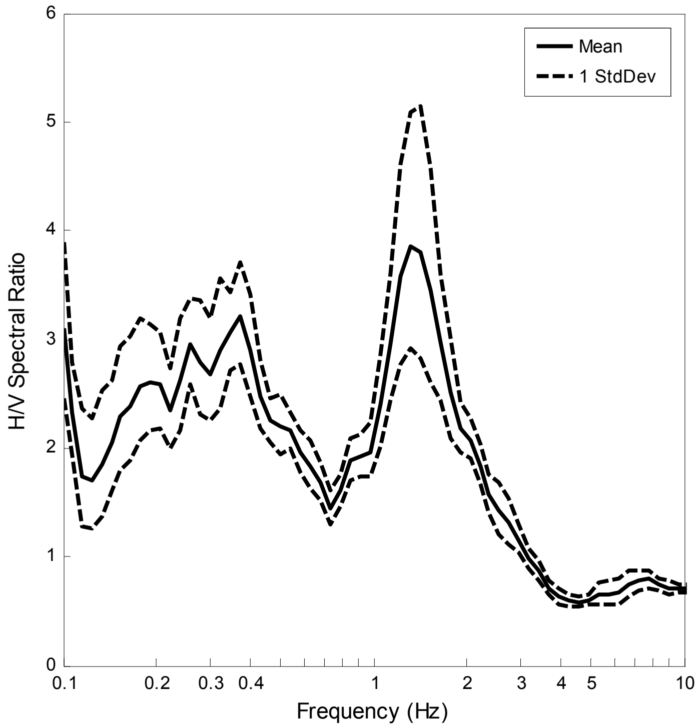
Depth: 33.5 m



Depth (m)	V_S (m/s)
0.0	380
0.1	130
3.5	185
17.5	145
22.0	350
33.5	

Horizontal-to-vertical (H/V) spectral ratio (CHHC_HV1)

Latitude Longitude (WGS 84):	-43.535113 172.627160
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.5 Cashmere High School (CMHS)

Nearby Geotechnical Site Investigation

Table 14 CMHS geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	3	Deep V_s profiling at site
H/V (HV)	1	

Figure 51 CMHS geotechnical site investigation location plan

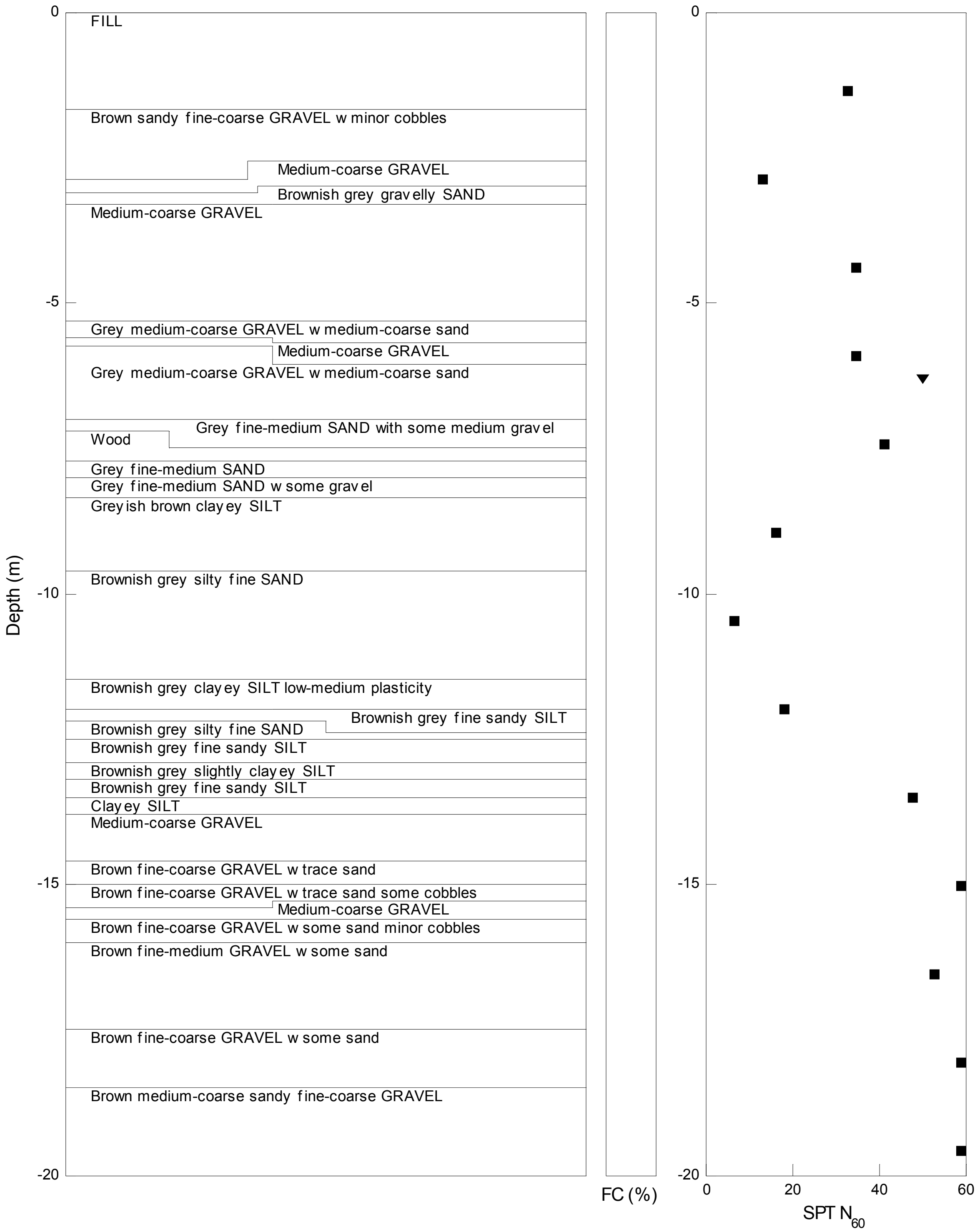
Borehole (CMHS_BH1)

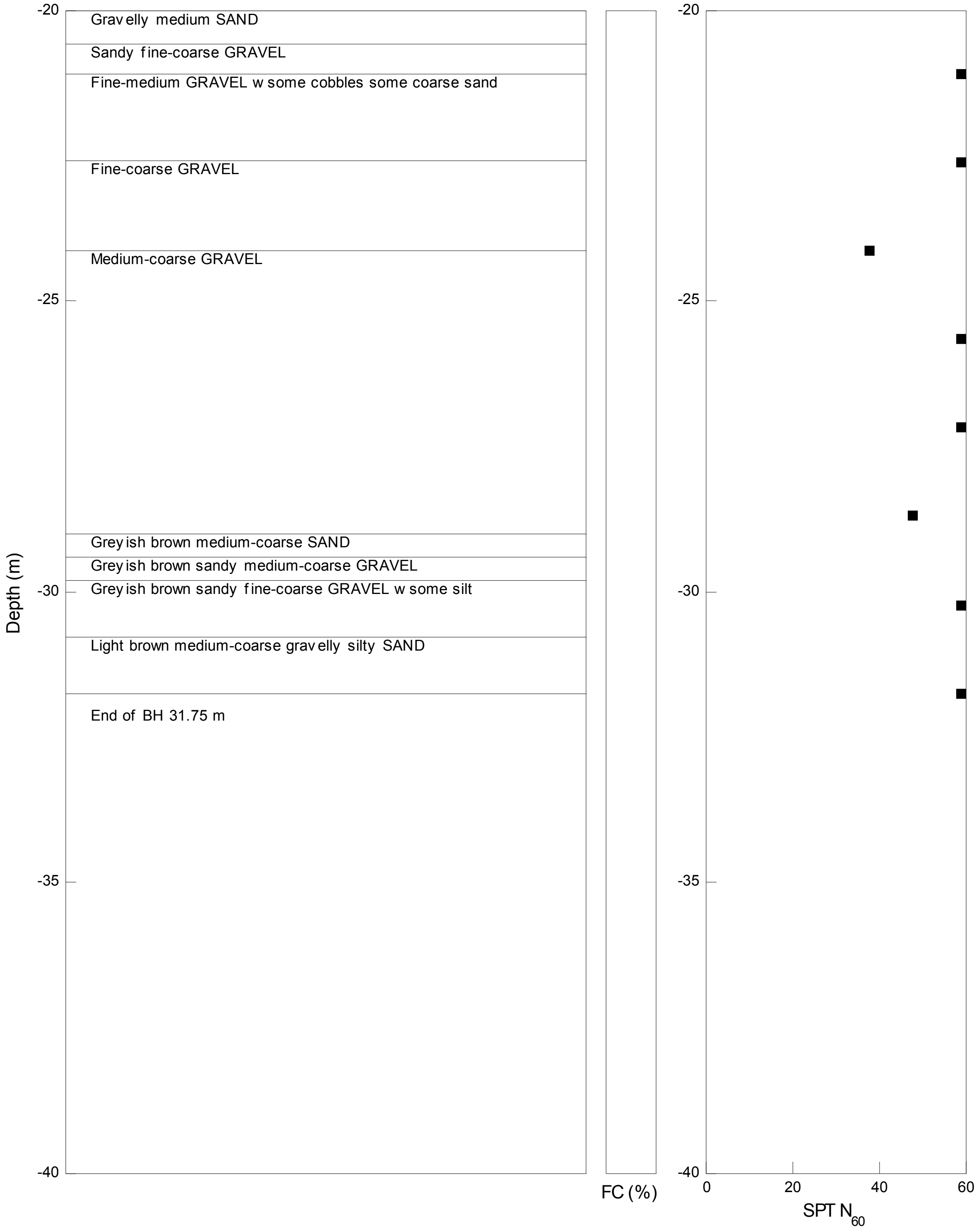
Latitude Longitude (WGS 84): -43.565204 172.624269

Drilling method : Sonic core

Water table depth: 2.0 m

Depth: 31.75 m

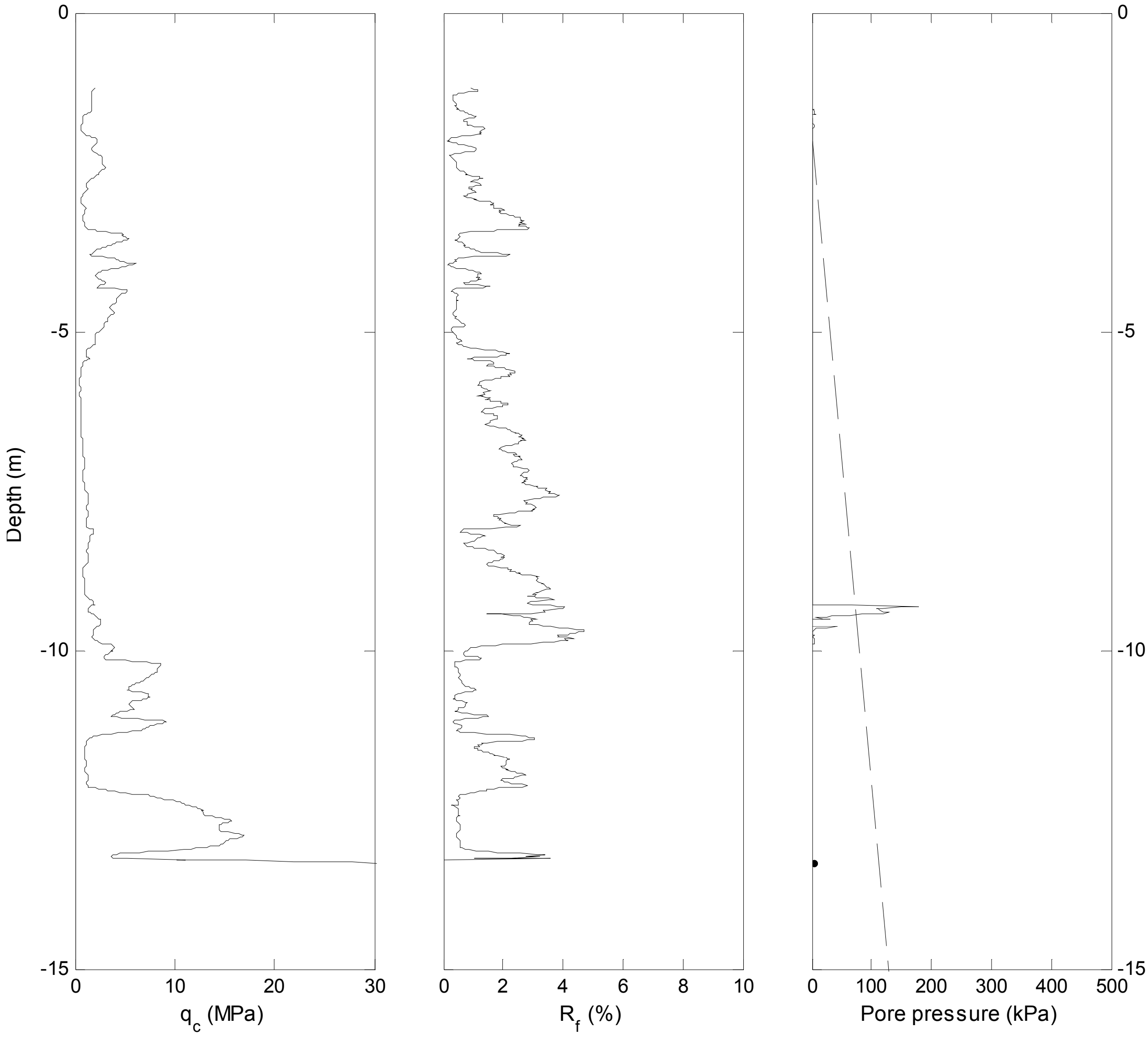




Gravelly medium SAND
Sandy fine-coarse GRAVEL
Fine-medium GRAVEL w some cobbles some coarse sand
Fine-coarse GRAVEL
Medium-coarse GRAVEL
Greyish brown medium-coarse SAND
Greyish brown sandy medium-coarse GRAVEL
Greyish brown sandy fine-coarse GRAVEL w some silt
Light brown medium-coarse gravelly silty SAND
End of BH 31.75 m
Depth (m)
-20
-25
-30
-35
-40
FC (%)
SPT N60
0
20
40
60

Cone Penetrometer (CMHS_CPT1)

Latitude Longitude (WGS 84):	-43.565262 172.626173
Water table depth:	2 m
Predrilled:	1.2 m
Depth:	13.34 m



Shear Wave Profile (CMHS_SW1)

Latitude Longitude (WGS 84): -43.565733 172.624583

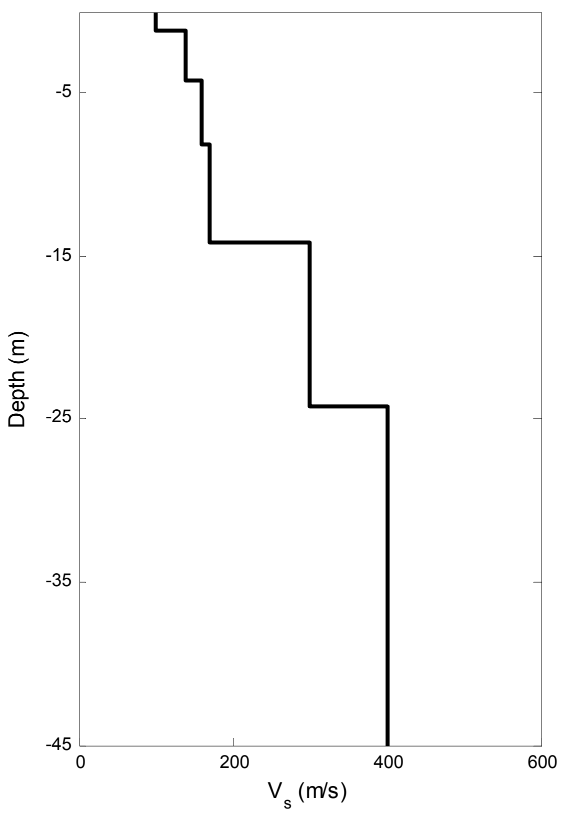
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

Depth: 45.0 m



Depth (m)	V_S (m/s)
0.0	99
1.2	140
4.2	160
8.2	170
14.2	300
24.2	400
44.2	

Shear Wave Profile (CMHS_SW2)

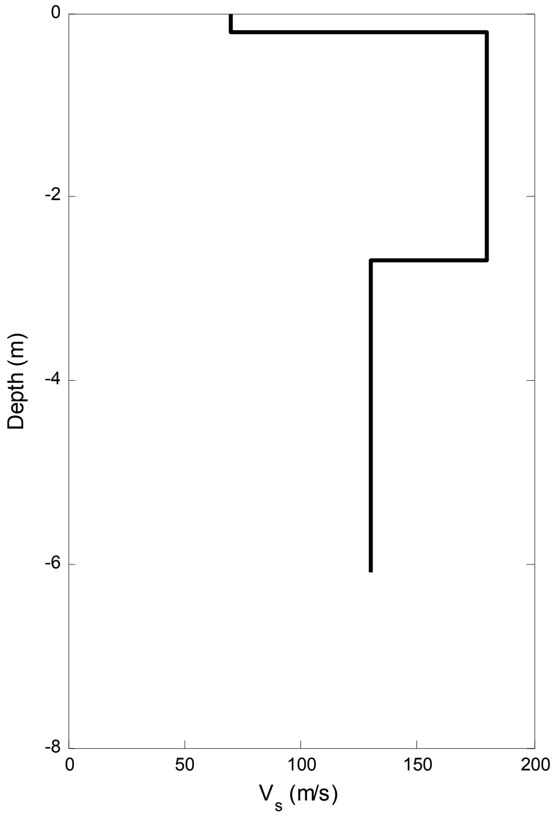
Latitude Longitude (WGS 84): -43.564667 172.624340

Methods: Active source (SASW) - 4.5 Hz vertical geophones

SASW geophone spacings: 0.61 m, 1.22 m, 2.44 m, 4.88 m, 6.1 m, 12.2 m

Source: Minimum of five sledgehammer impacts per offset

Depth: 6.1 m



Depth (m)	V_S (m/s)
0.0	70
0.2	180
2.7	130
6.1	

Shear Wave Profile (CMHS_SW3)

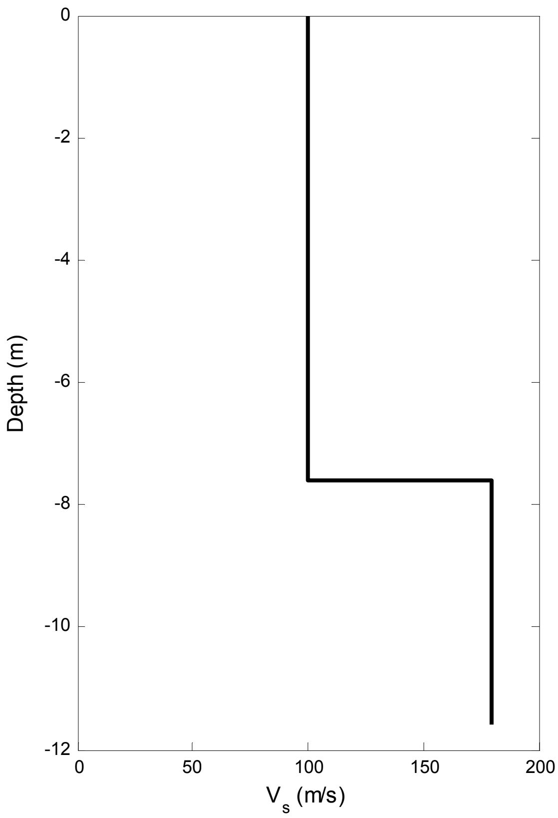
Latitude Longitude (WGS 84): -43.564916 172.625084

Methods: Active source (SASW) - 4.5 Hz vertical geophones

SASW geophone spacings: 0.61 m, 1.22 m, 2.44 m, 4.88 m, 6.1 m, 12.2 m

Source: Minimum of five sledgehammer impacts per offset

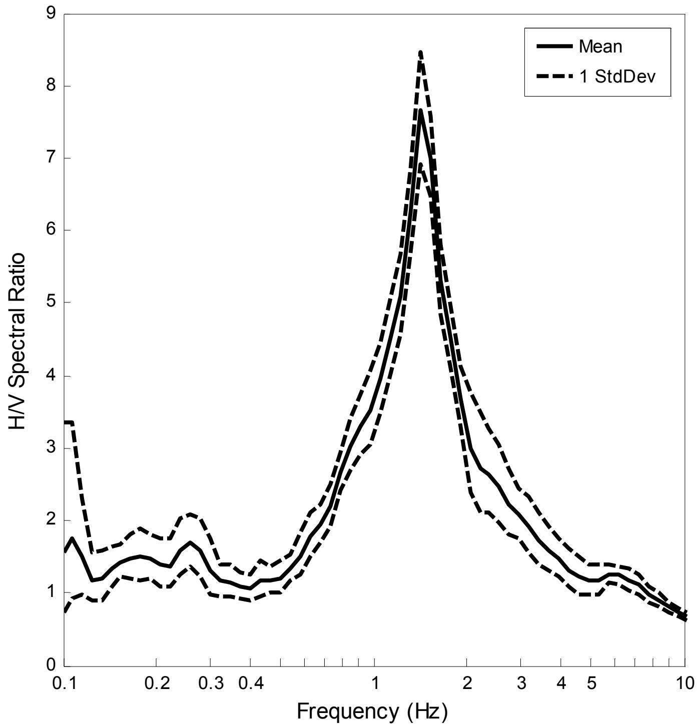
Depth: 11.6 m



Depth (m)	V_S (m/s)
0.0	100
7.6	180
11.6	

Horizontal-to-vertical (H/V) spectral ratio (CMHS_HV1)

Latitude Longitude (WGS 84):	-43.565800 172.624124
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.6 Hulverstone Drive Pumping Station (HPSC)

Nearby Geotechnical Site Investigation

Table 15 HPSC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	
H/V (HV)	1	

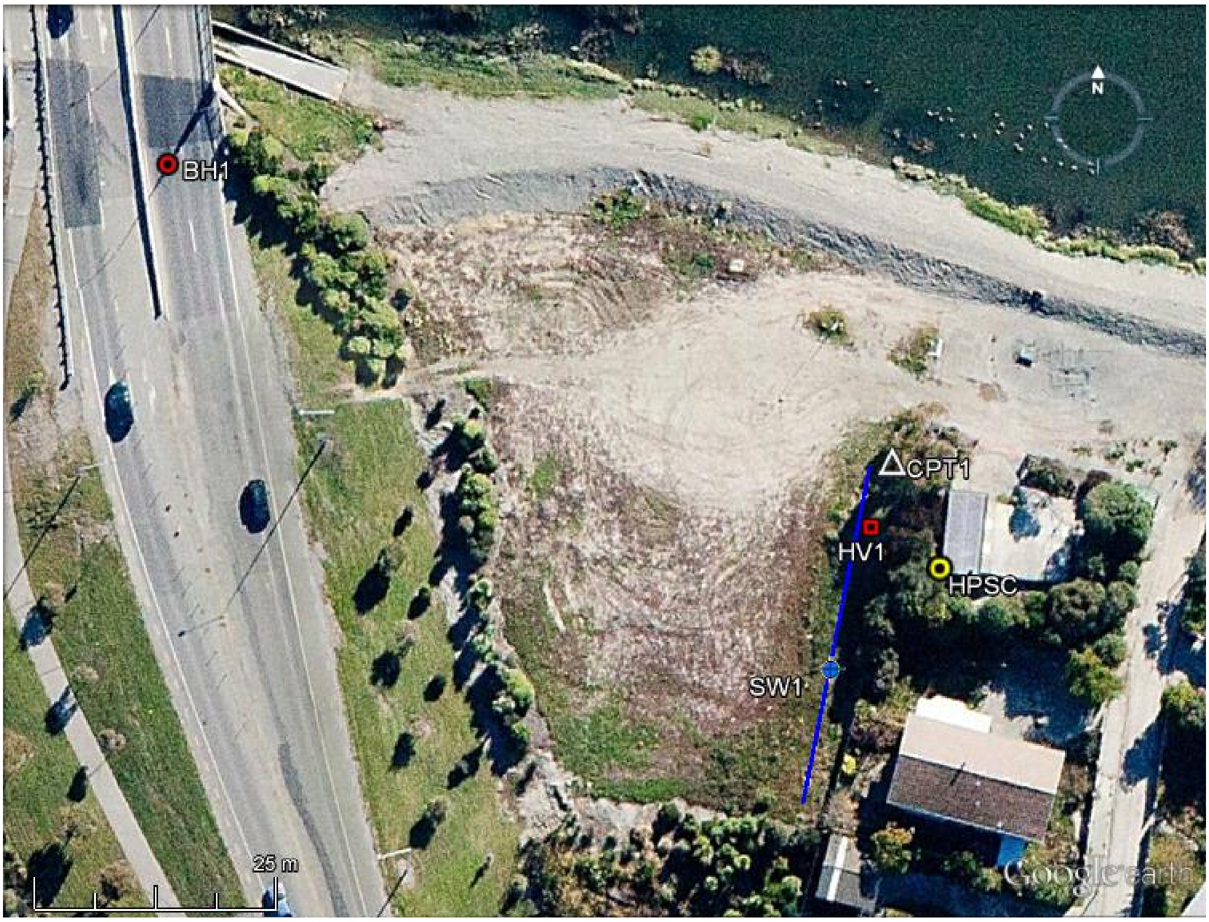
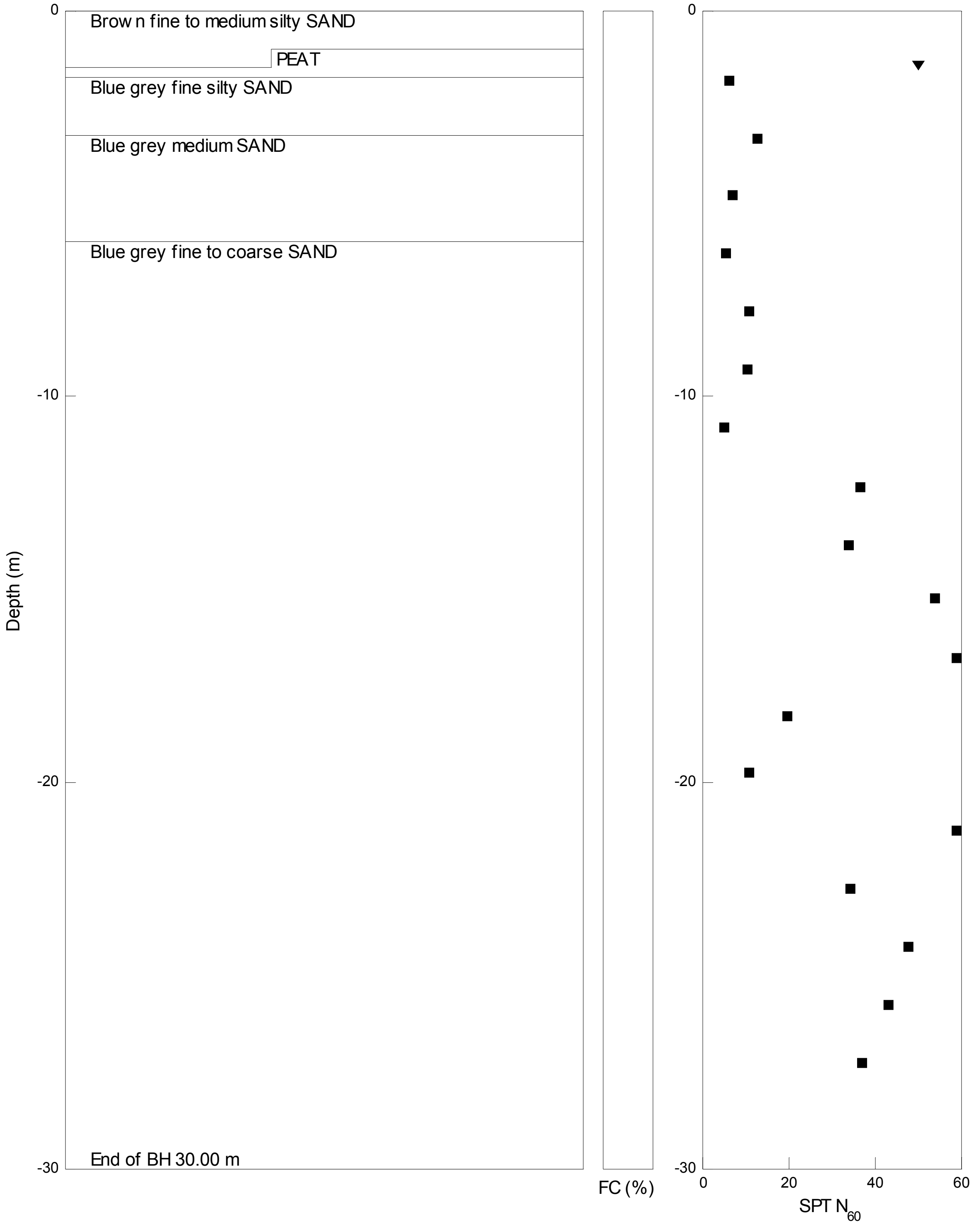


Figure 52 HPSC geotechnical site investigation location plan

Borehole (HPSC_BH1)

Latitude Longitude (WGS 84):	-43.501199 172.701203
Drilling method :	Cable Tool
Water table depth:	1.5 m
Depth:	30 m



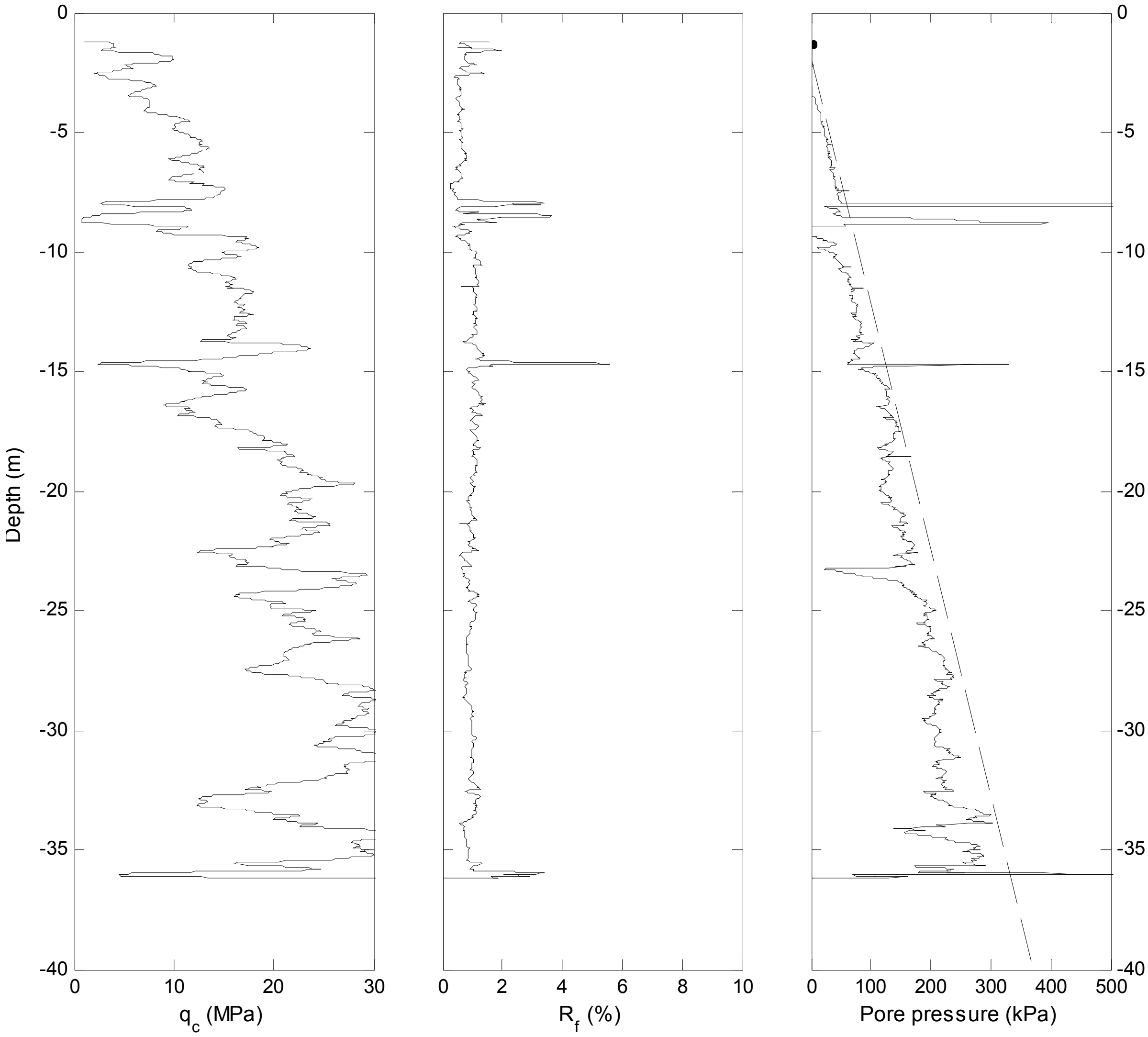
Cone Penetrometer (HPSC_CPT1)

Latitude Longitude (WGS 84): -43.501474 172.702128

Water table depth: 2 m

Predrilled: 1.2 m

Depth: 36.23 m



Shear Wave Profile (HPSC_SW1)

Latitude Longitude (WGS 84): -43.501667 172.702050

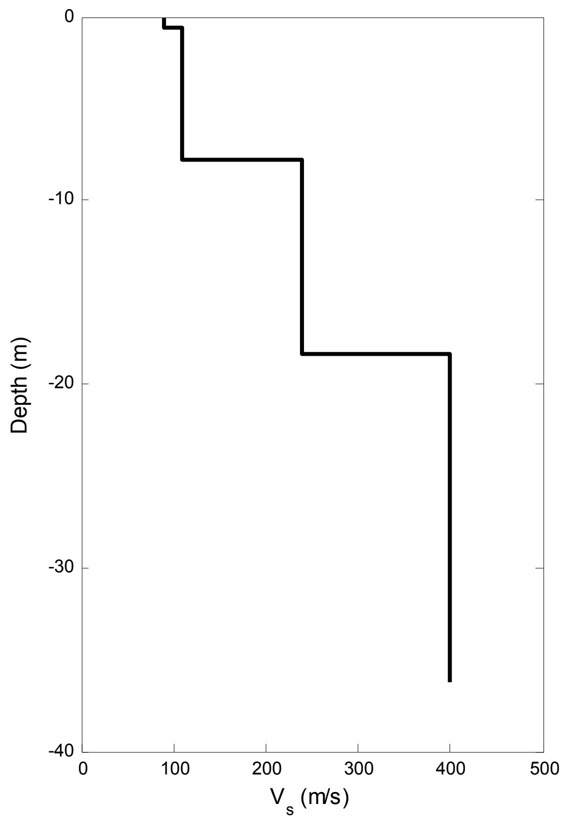
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

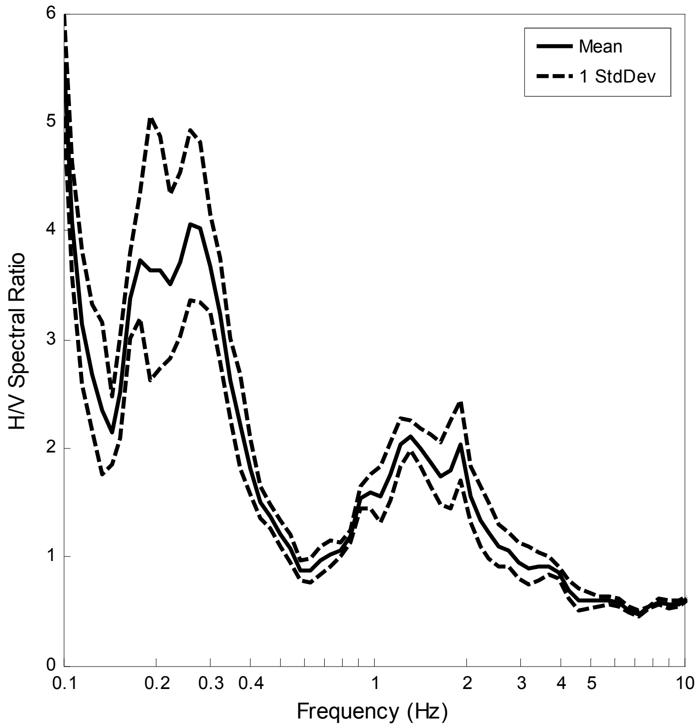
Depth: 36.2 m



Depth (m)	V_S (m/s)
0.0	90
0.6	110
7.8	240
18.4	400
36.2	

Horizontal-to-vertical (H/V) spectral ratio (HPSC_HV1)

Latitude Longitude (WGS 84):	-43.501534 172.702102
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.7 Heathcote Valley Primary School (HVSC)

Nearby Geotechnical Site Investigation

Table 16 HVSC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	5	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V (HV)	1	

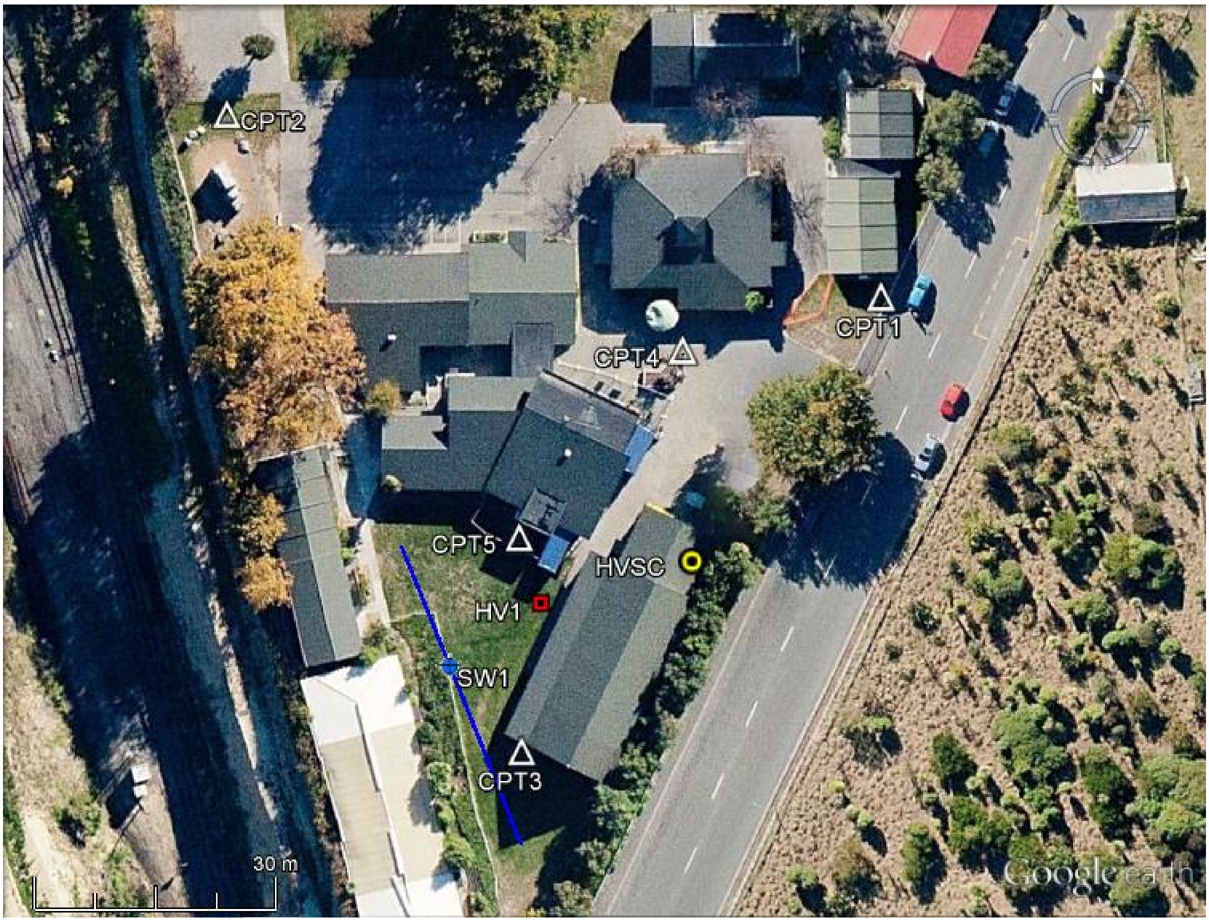


Figure 53 HVSC geotechnical site investigation location plan

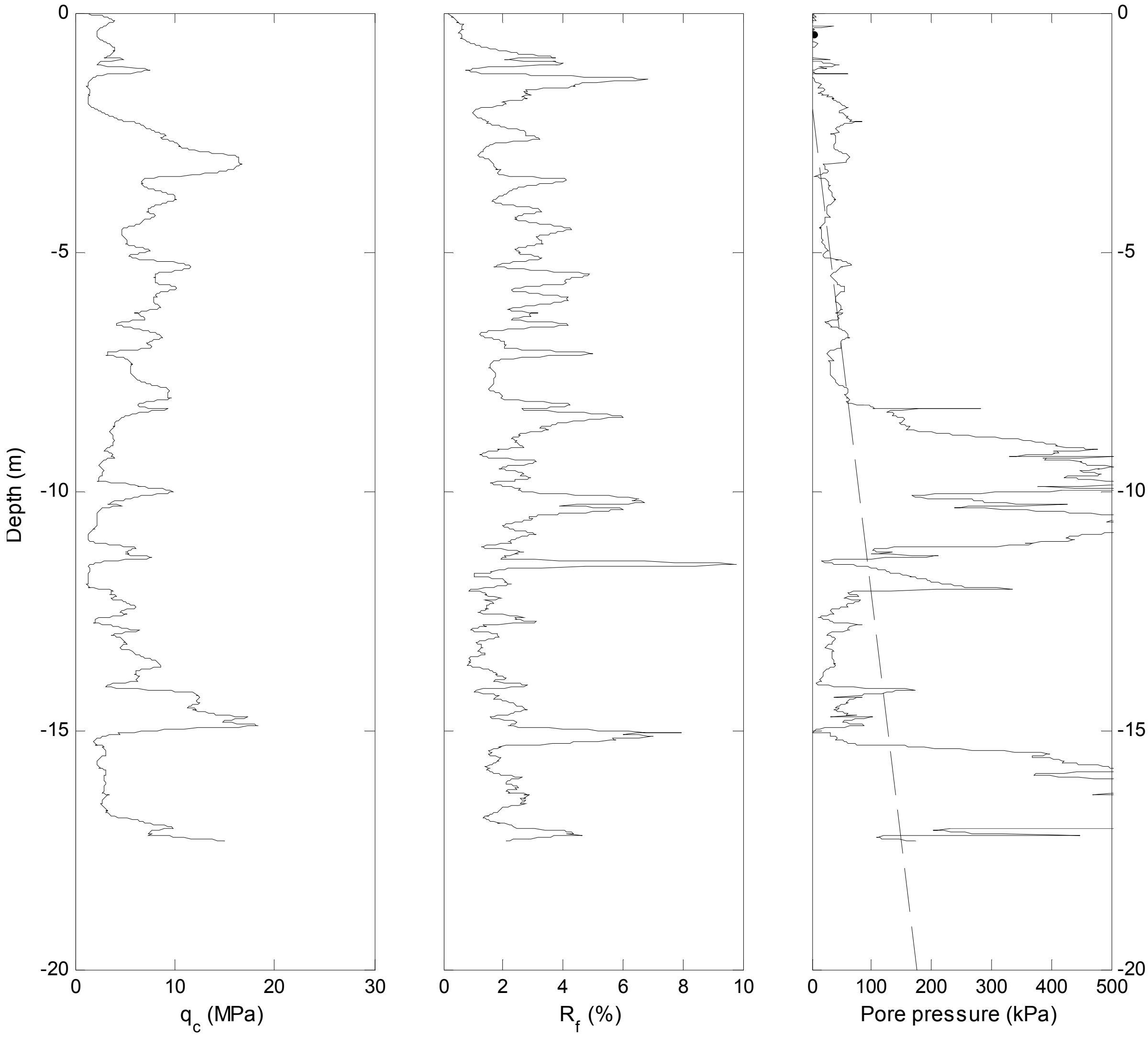
Cone Penetrometer (HVSC_CPT1)

Latitude Longitude (WGS 84): -43.579492 172.709702

Water table depth: 2 m

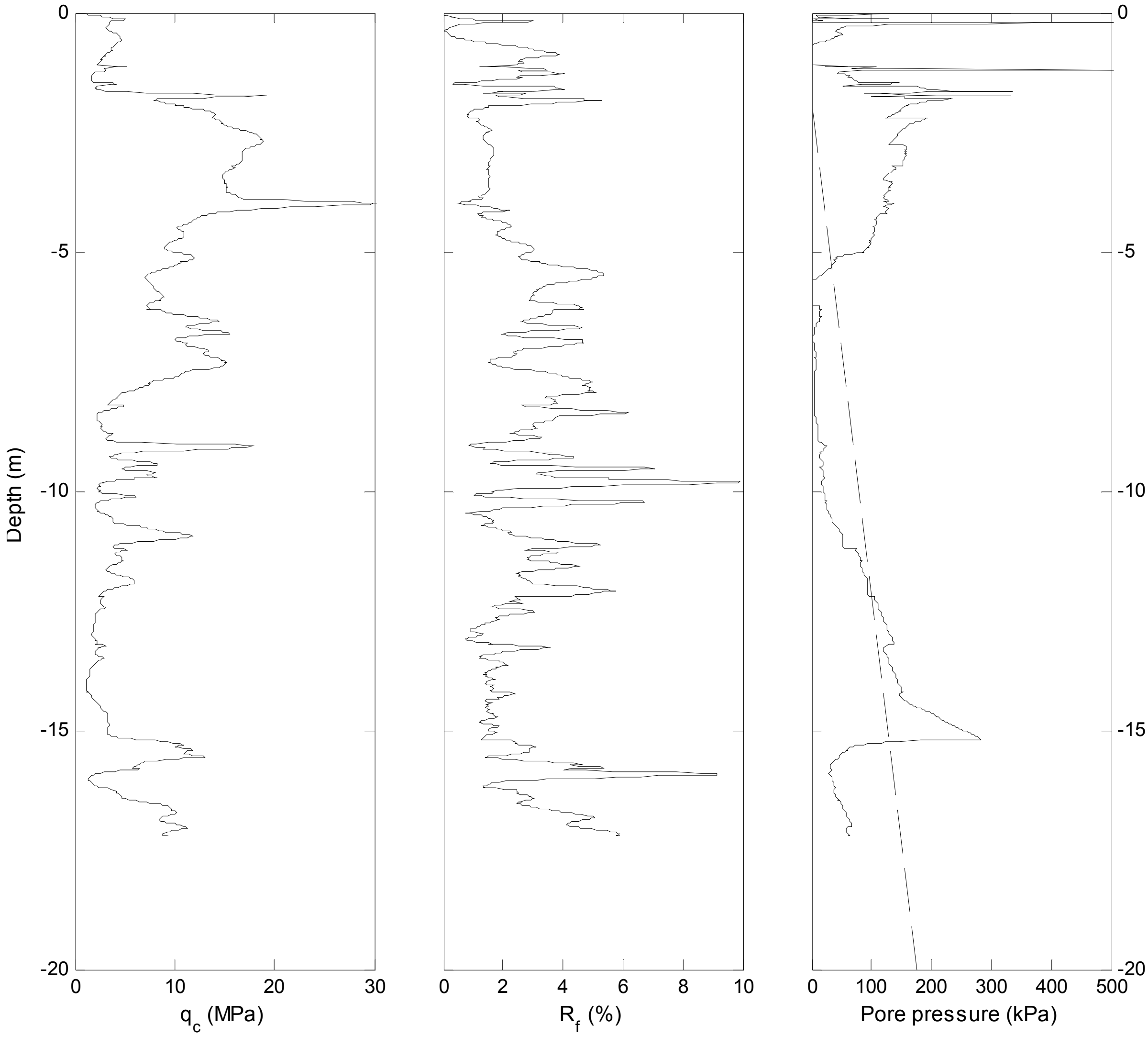
Predrilled: 0 m

Depth: 17.31 m



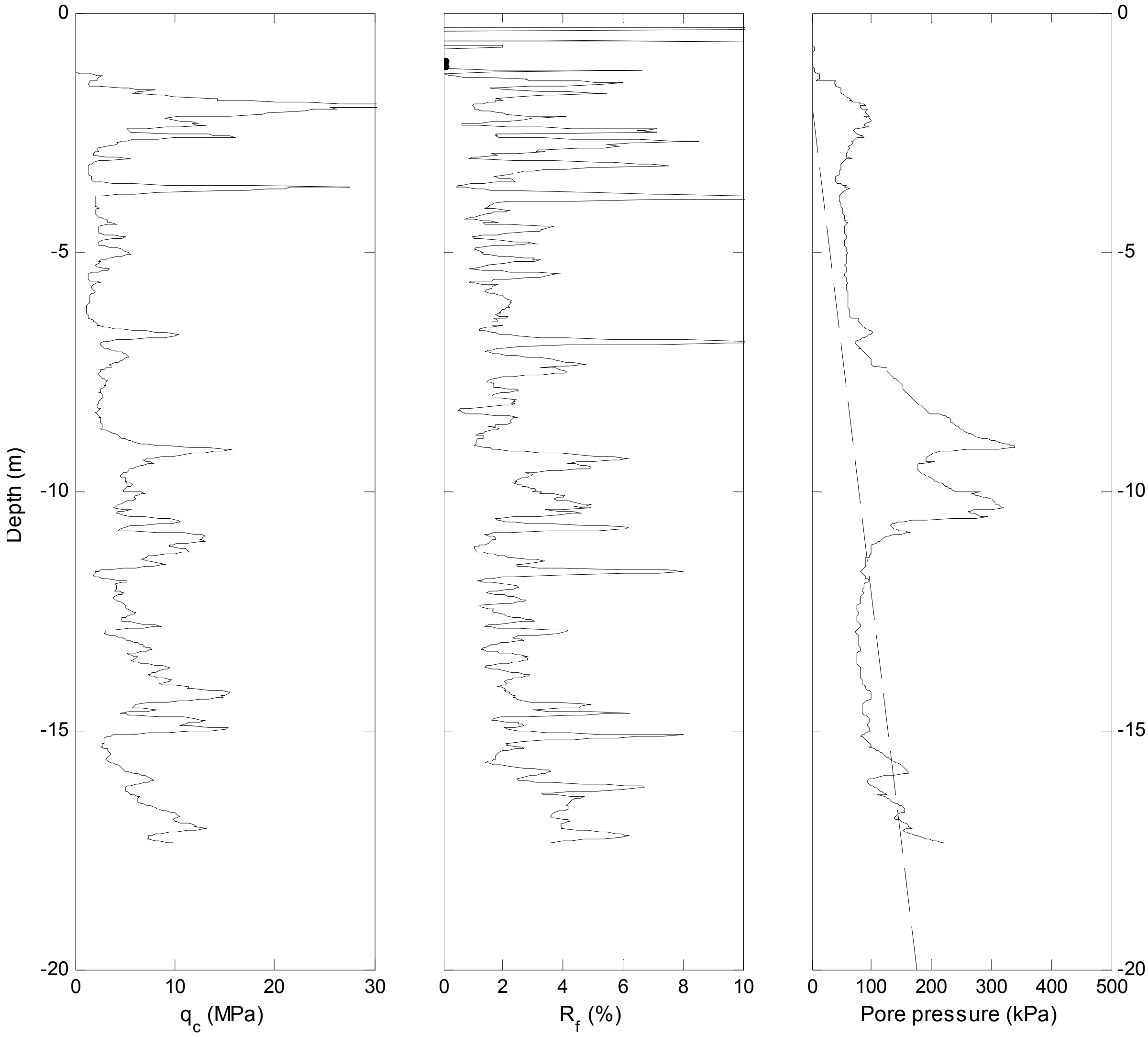
Cone Penetrometer (HVSC_CPT2)

Latitude Longitude (WGS 84):	-43.579279 172.708698
Water table depth:	2 m
Predrilled:	0 m
Depth:	17.21 m



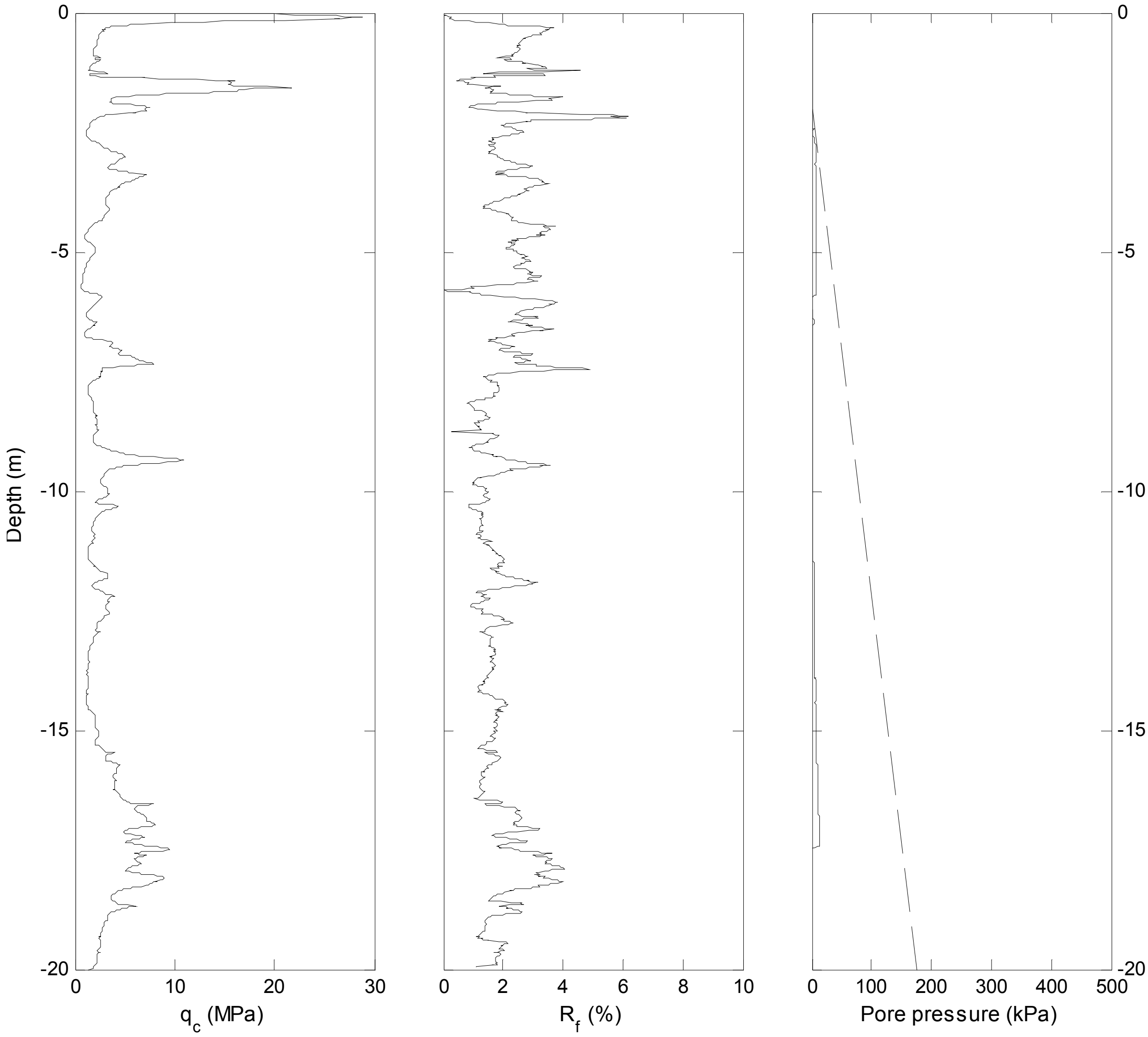
Cone Penetrometer (HVSC_CPT3)

Latitude Longitude (WGS 84):	-43.579994 172.709162
Water table depth:	2 m
Predrilled:	1.2 m
Depth:	17.36 m



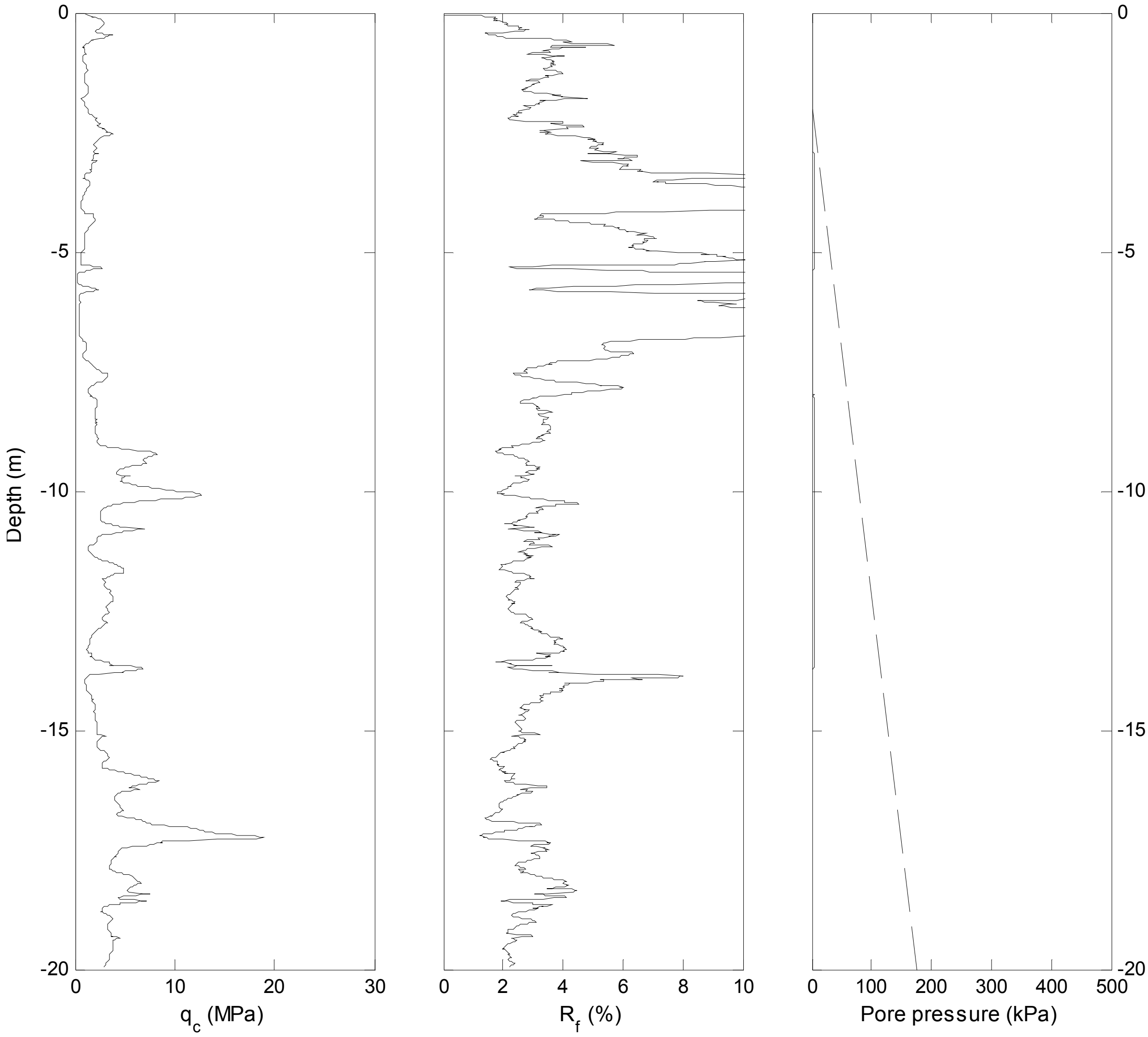
Cone Penetrometer (HVSC_CPT4)

Latitude Longitude (WGS 84):	-43.579549 172.709406
Water table depth:	2 m
Predrilled:	0 m
Depth:	20.00 m



Cone Penetrometer (HVSC_CPT5)

Latitude Longitude (WGS 84):	-43.579755 172.709157
Water table depth:	2 m
Predrilled:	0 m
Depth:	19.93 m



Shear Wave Profile (HPSC_SW1)

Latitude Longitude (WGS 84): -43.579900 172.709050

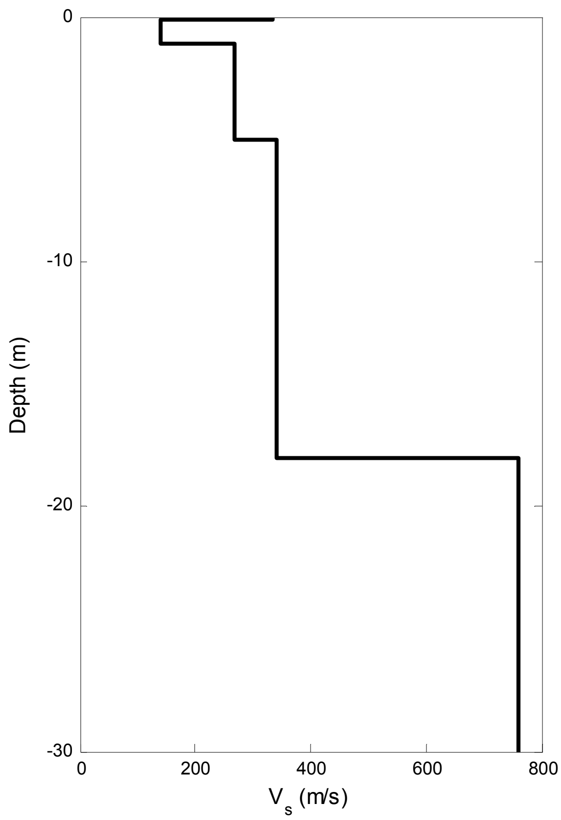
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

Depth: 30 m



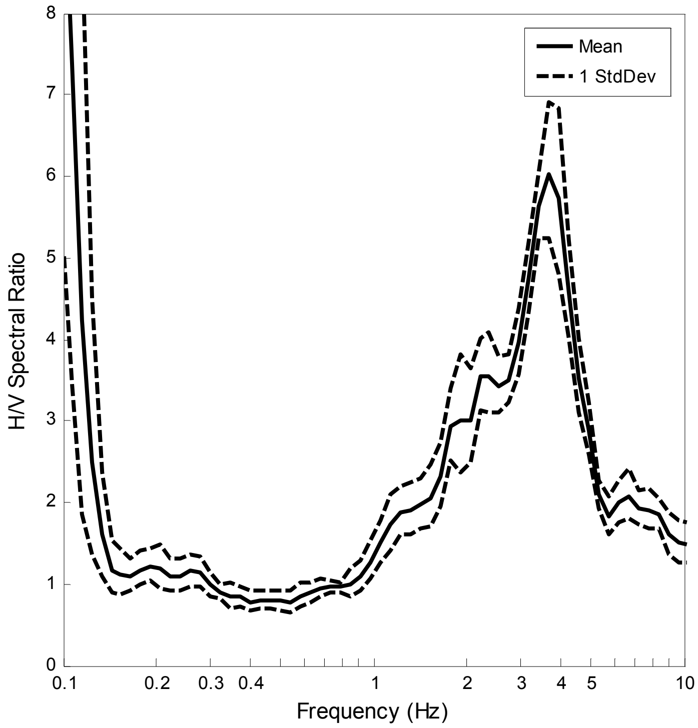
Depth (m)	V_S (m/s)
0.0	335
0.1	140
1.1	270
5.0	340
18.0	760
30.0	

Horizontal-to-vertical (H/V) spectral ratio (HPSC_HV1)

Latitude Longitude (WGS 84): -43.579827 172.709192

Equipment: Nanometrics Trillium compact 120 second broadband seismometer

Record length: 1 hour



C.8 Kaiapoi North School (KPOC)

Nearby Geotechnical Site Investigation

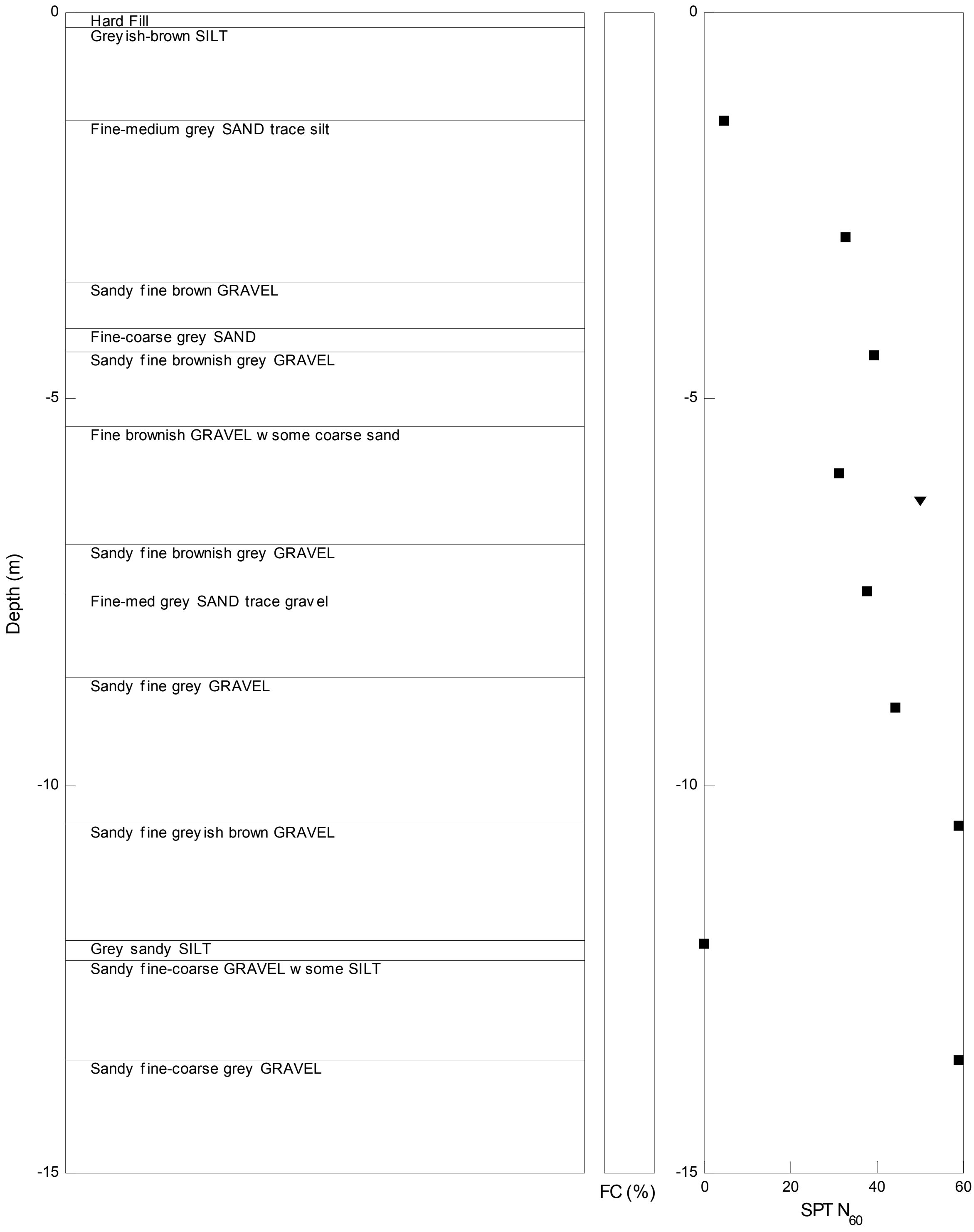
Table 17 KPOC geotechnical site investigation summary

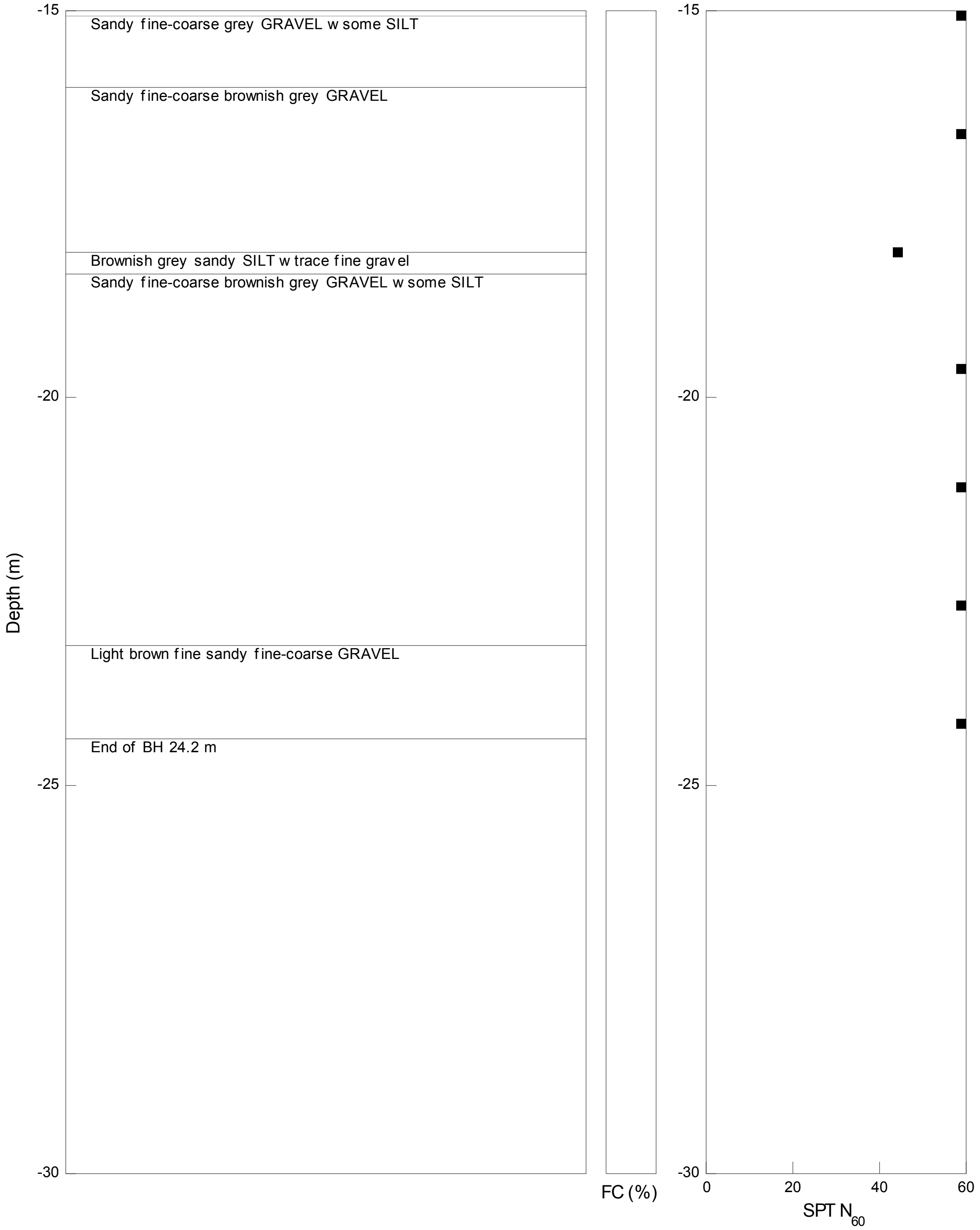
Investigation Method	Number	Notes
CPT (CPT)	0	Gravelly site
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	
H/V (HV)	1	

Figure 54 KPOC geotechnical site investigation location plan

Borehole (KPOC_BH1)

Latitude Longitude (WGS 84):	-43.376600 172.664324
Drilling method :	Sonic core
Water table depth:	1.2 m
Depth:	24.4 m

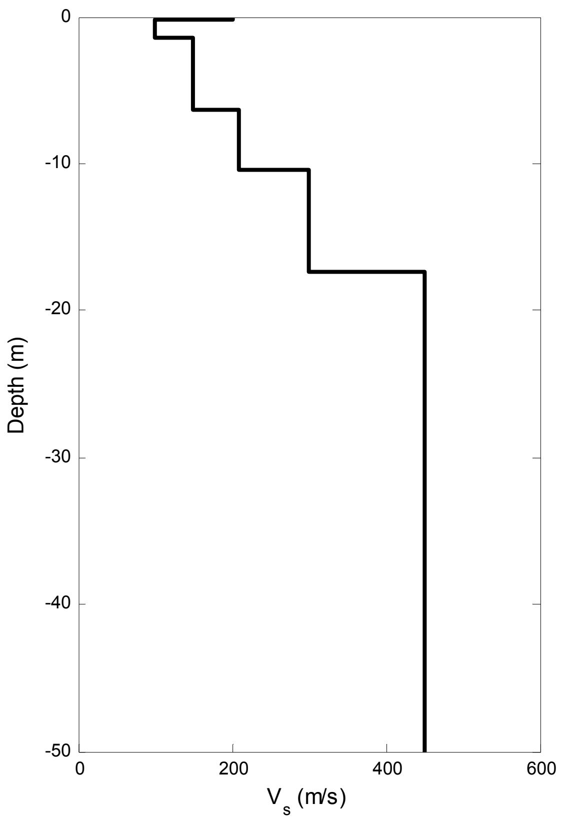




Depth (m)
-15
-20
-25
-30
Sandy fine-coarse grey GRAVEL w some SILT
Sandy fine-coarse brownish grey GRAVEL
Brownish grey sandy SILT w trace fine gravel
Sandy fine-coarse brownish grey GRAVEL w some SILT
Light brown fine sandy fine-coarse GRAVEL
End of BH 24.2 m
FC (%)
0
20
40
60
SPT N_{60}

Shear Wave Profile (KPOC_SW1)

Latitude Longitude (WGS 84):	-43.376283 172.664433
Methods:	Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing. Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.
MASW Source offsets:	4.6 m, 9.1m, 18.3 m
Source:	Minimum of five sledgehammer impacts per offset
Depth:	50.0 m



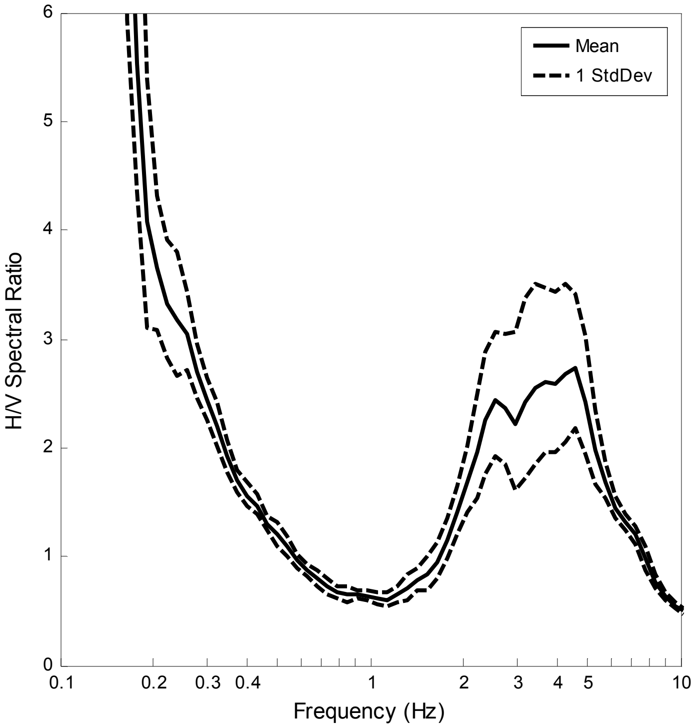
Depth (m)	V_S (m/s)
0.0	200
0.2	100
1.4	150
6.4	210
10.4	300
17.4	450
50.0	

Horizontal-to-vertical (H/V) spectral ratio (KPOC_HV1)

Latitude Longitude (WGS 84): -43.376563 172.664213

Equipment: Trillium compact 120 second broadband seismometer

Record length: 1 hour



C.9 New Brighton Library (NBLC)

Nearby Geotechnical Site Investigation

Table 18 NBLC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V (HV)	1	

Figure 55 NBLC geotechnical site investigation location plan

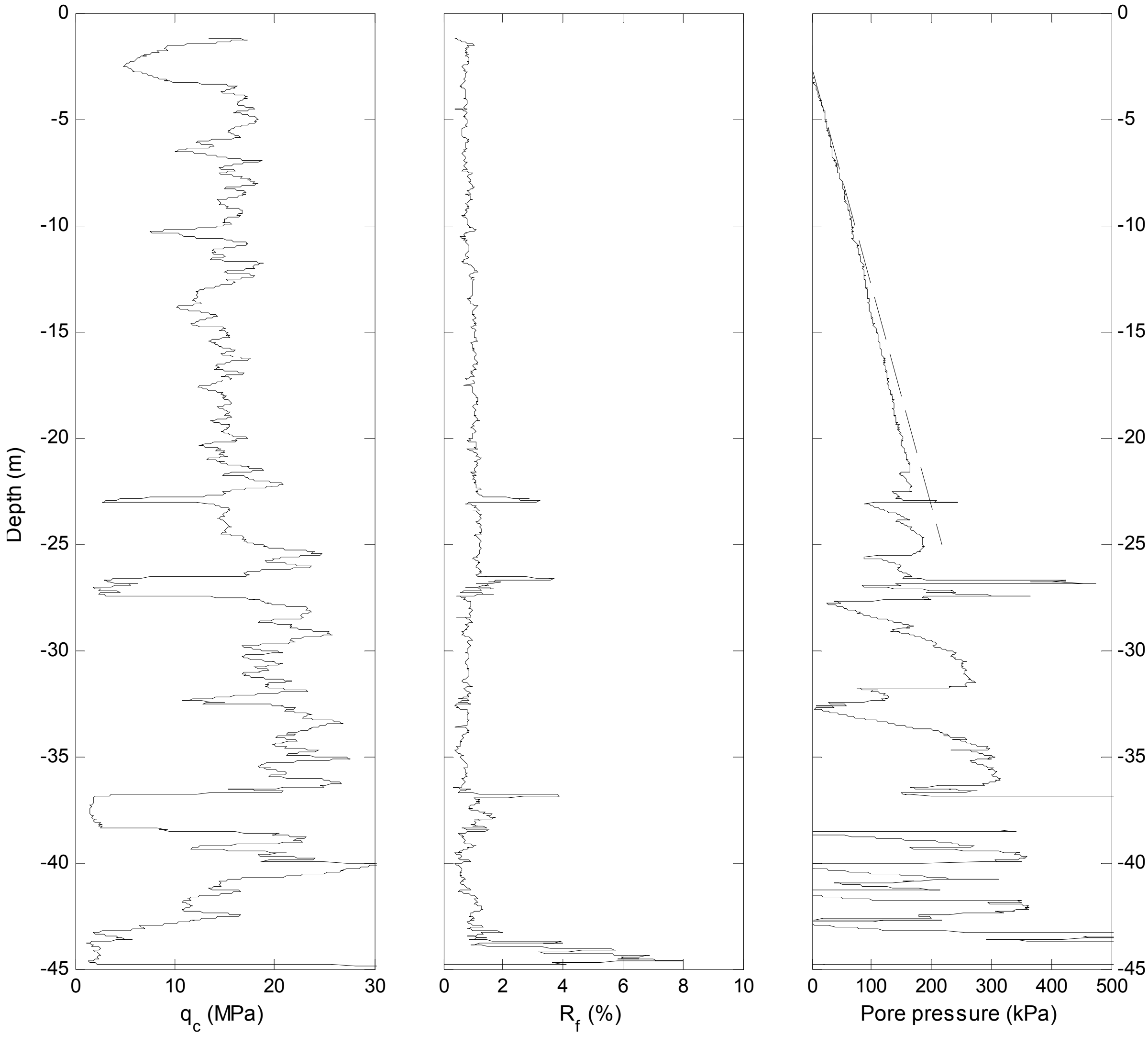
Cone Penetrometer (NBLC_CPT1)

Latitude Longitude (WGS 84): -43.506421 172.731111

Water table depth: 2.7 m

Predrilled: 1.2 m

Depth: 44.86 m



Shear Wave Profile (NBLC_SW1)

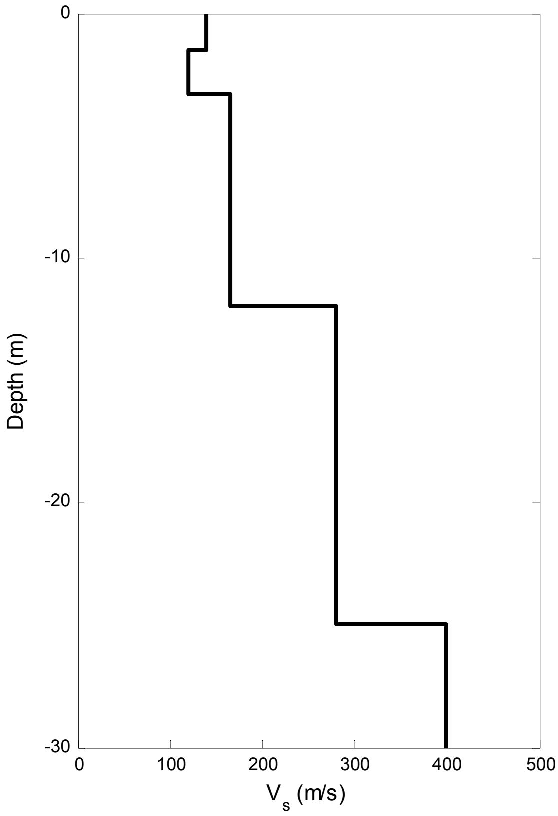
Latitude Longitude (WGS 84): -43.506135 172.730842

Methods: Active source (MASW, SASW) - Linear array of 24 4.5 Hz vertical geophones @ 2 m spacing.

MASW Source offsets: 5 m, 10 m, 20 m

Source: Minimum of five sledgehammer impacts per offset

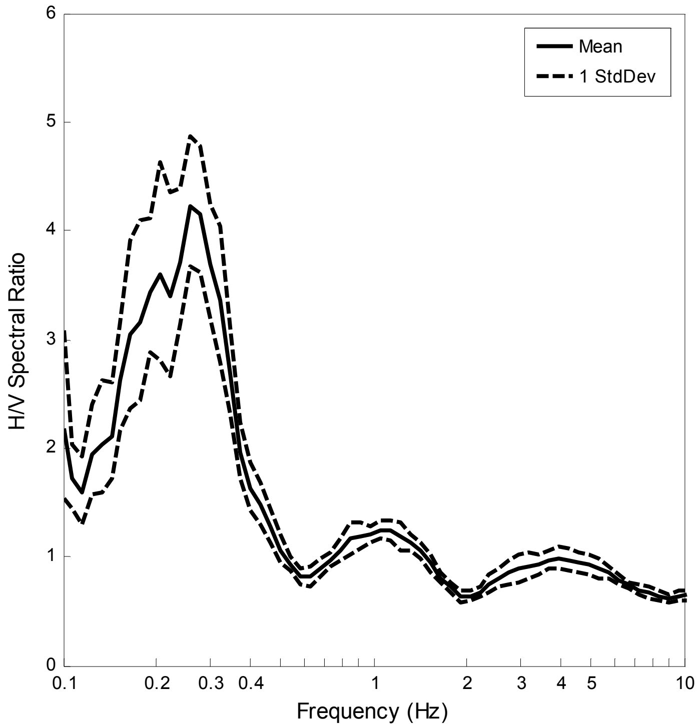
Depth: 30 m



Depth (m)	V_S (m/s)
0.0	140
1.5	120
3.3	165
12.0	280
25.0	400
45.0	

Horizontal-to-vertical (H/V) spectral ratio (NBLC_HV1)

Latitude Longitude (WGS 84):	-43.506496 172.730962
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.10 North New Brighton School (NNBS)

Nearby Geotechnical Site Investigation

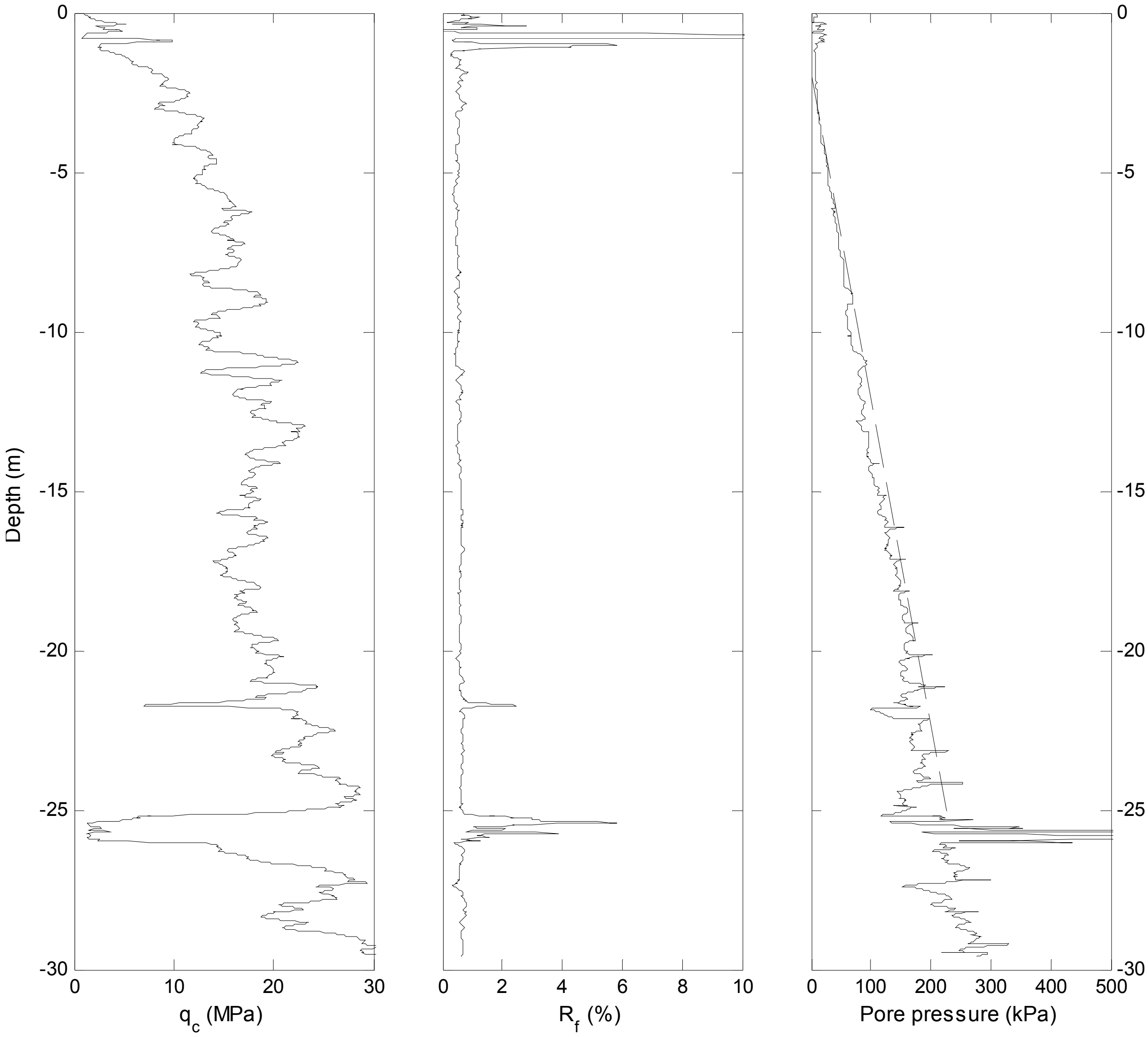
Table 19 NNBS geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	2	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V (HV)	1	

Figure 56 NNBS geotechnical site investigation location plan

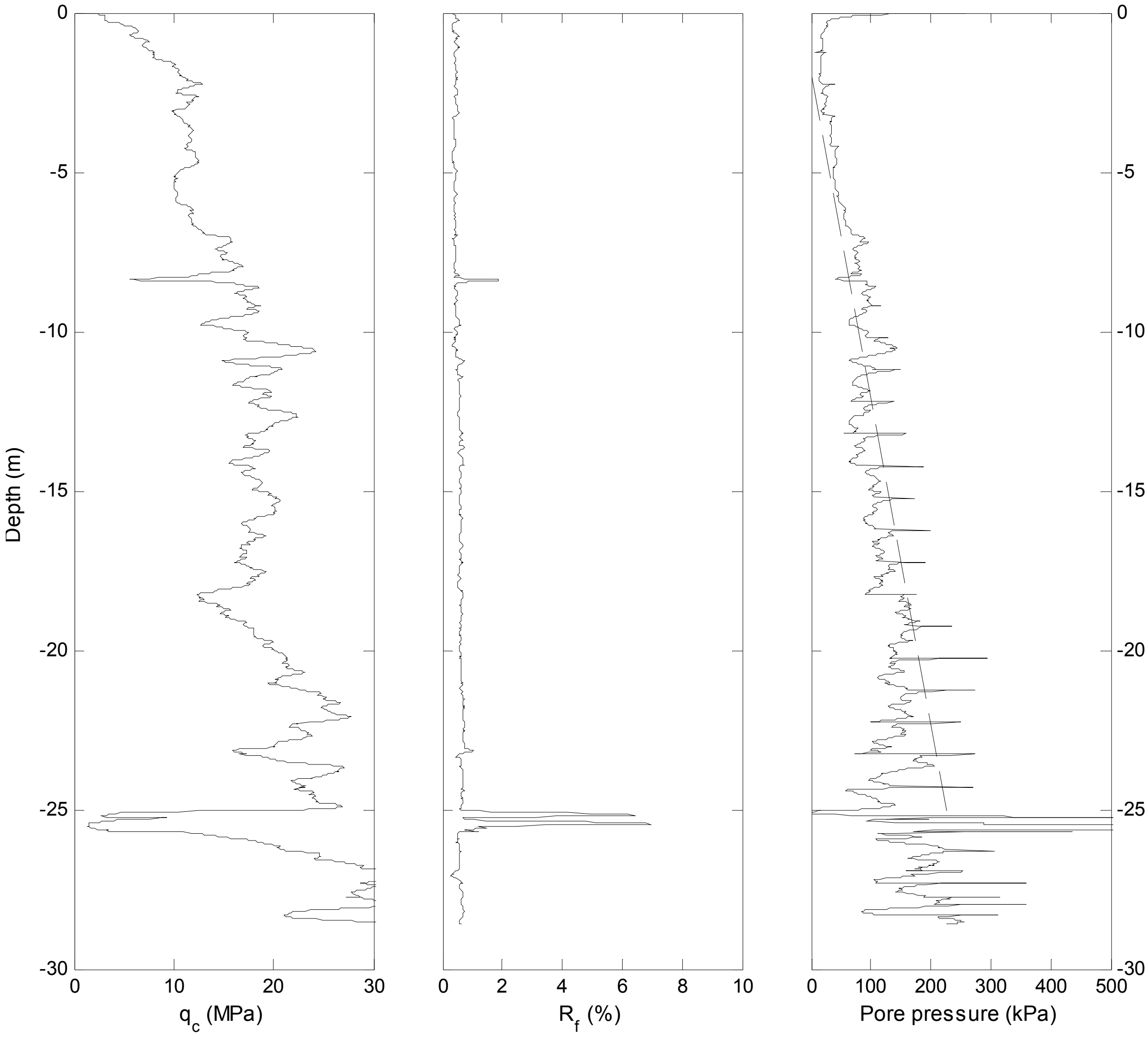
Cone Penetrometer (NNBS_CPT1)

Latitude Longitude (WGS 84):	-43.495286 172.718085
Water table depth:	2.0 m
Predrilled:	0.0 m
Depth:	29.59 m



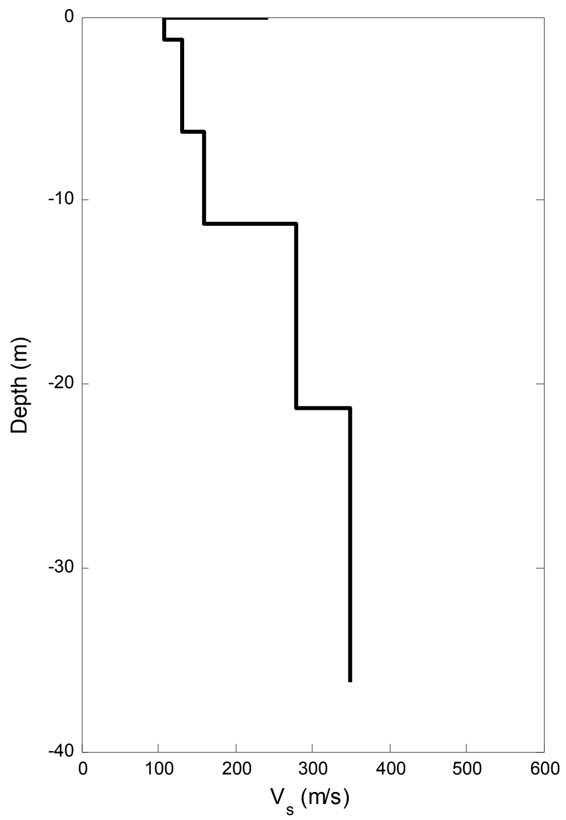
Cone Penetrometer (NNBS_CPT2)

Latitude Longitude (WGS 84):	-43.494925 172.717991
Water table depth:	2.0 m
Predrilled:	0.0 m
Depth:	28.61 m



Shear Wave Profile (NNBS_SW1)

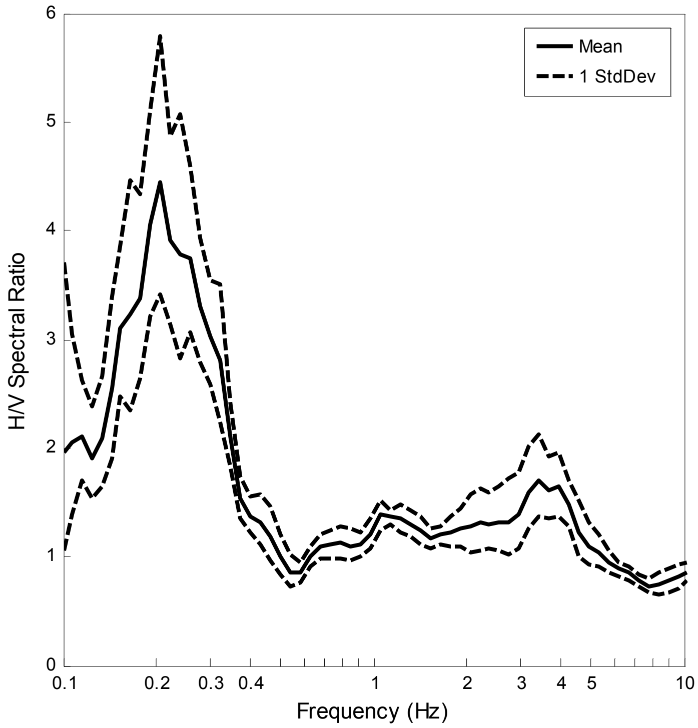
Latitude Longitude (WGS 84):	-43.495067 172.718117
Methods:	Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing. Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.
MASW Source offsets:	4.6 m, 9.1m, 18.3 m
Source:	Minimum of five sledgehammer impacts per offset
Depth:	36.3 m



Depth (m)	V_S (m/s)
0.0	243
0.09	107
1.3	131
6.3	160
11.3	280
21.3	350
36.3	

Horizontal-to-vertical (H/V) spectral ratio (NNBS_HV1)

Latitude Longitude (WGS 84):	-43.495067 172.718117
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



Surrounding Geotechnical Site Investigations

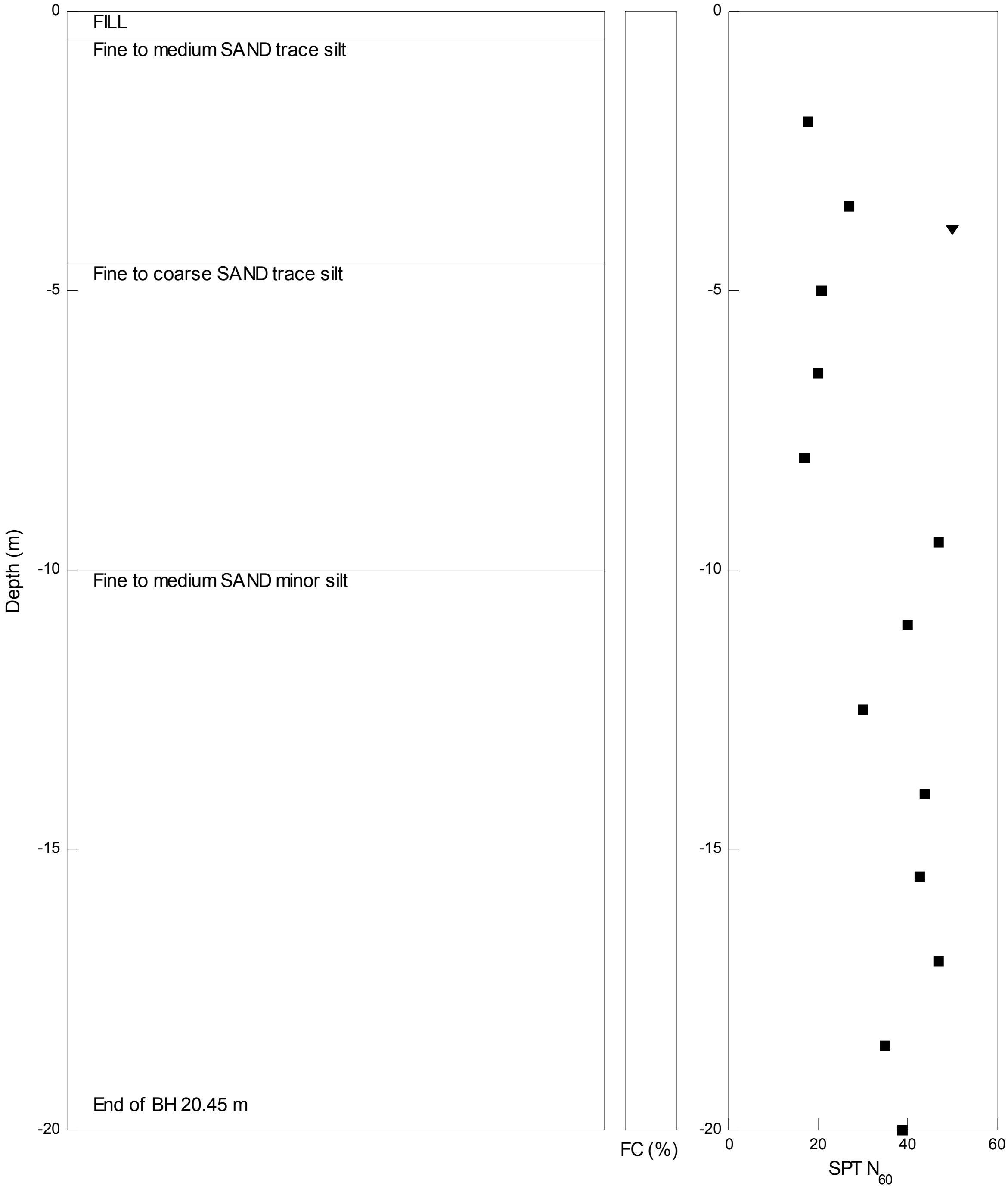
Table 20 NNBS surrounding geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	2	
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	0	
H/V Spectral Ratio (HV)	0	

Figure 57 NNBS surrounding geotechnical site investigation location plan

Borehole (NNBS_BHS1)

Latitude Longitude (WGS 84):	-43.495217 172.716523
Drilling method :	Mud Rotary
Water table depth:	4.0 m
Depth:	20.45 m



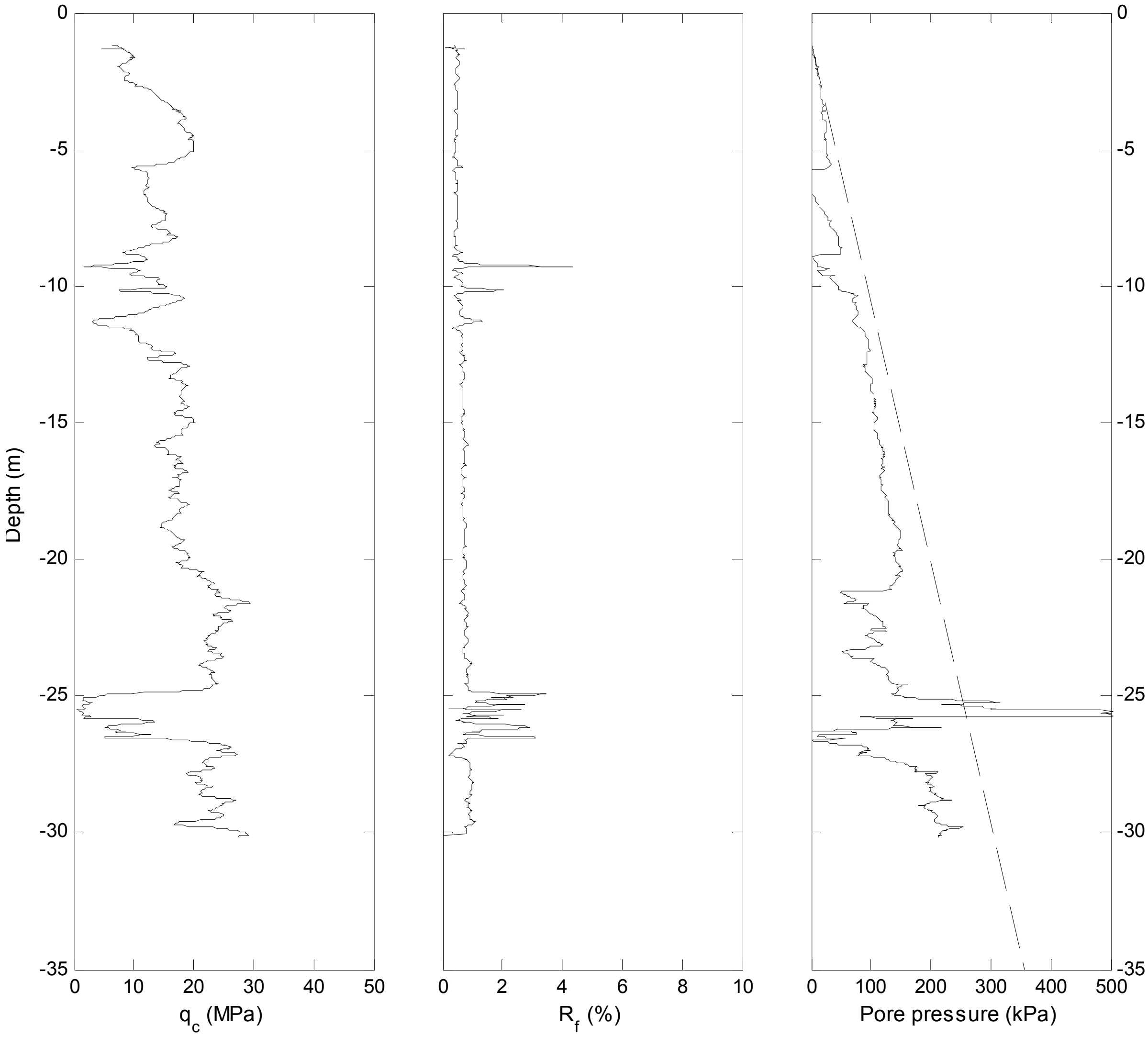
Cone Penetrometer (NNBS_CPTS1)

Latitude Longitude (WGS 84): -43.494248 172.719128

Water table depth: 1.2 m

Predrilled: 1.2 m

Depth: 30.14 m



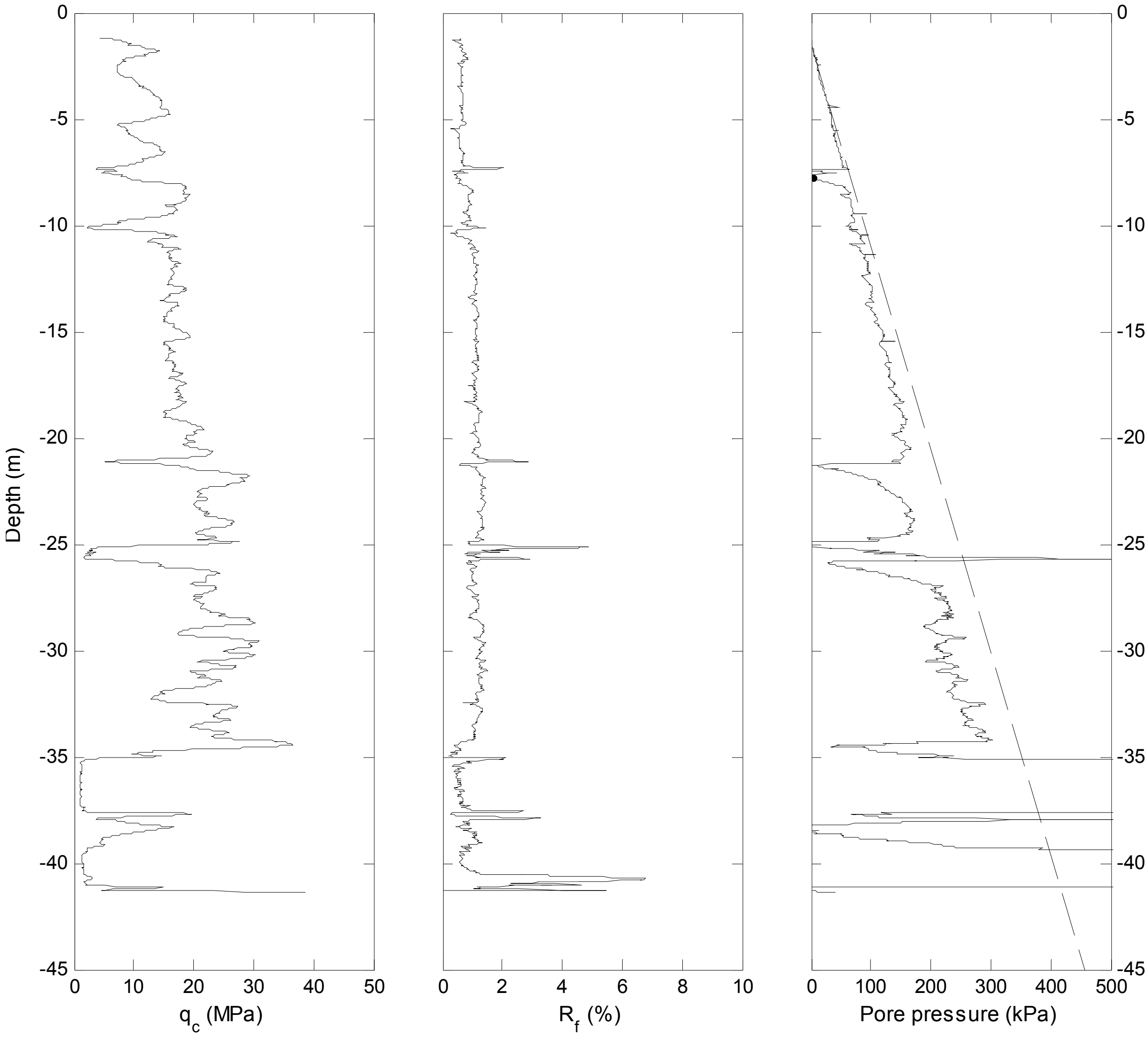
Cone Penetrometer (NNBS_CPTS2)

Latitude Longitude (WGS 84): -43.496084 172.718501

Water table depth: 1.6 m

Predrilled: 1.2 m

Depth: 41.36 m



C.11 Papanui High School (PPHS)

Nearby Geotechnical Site Investigation

Table 21 PPHS geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

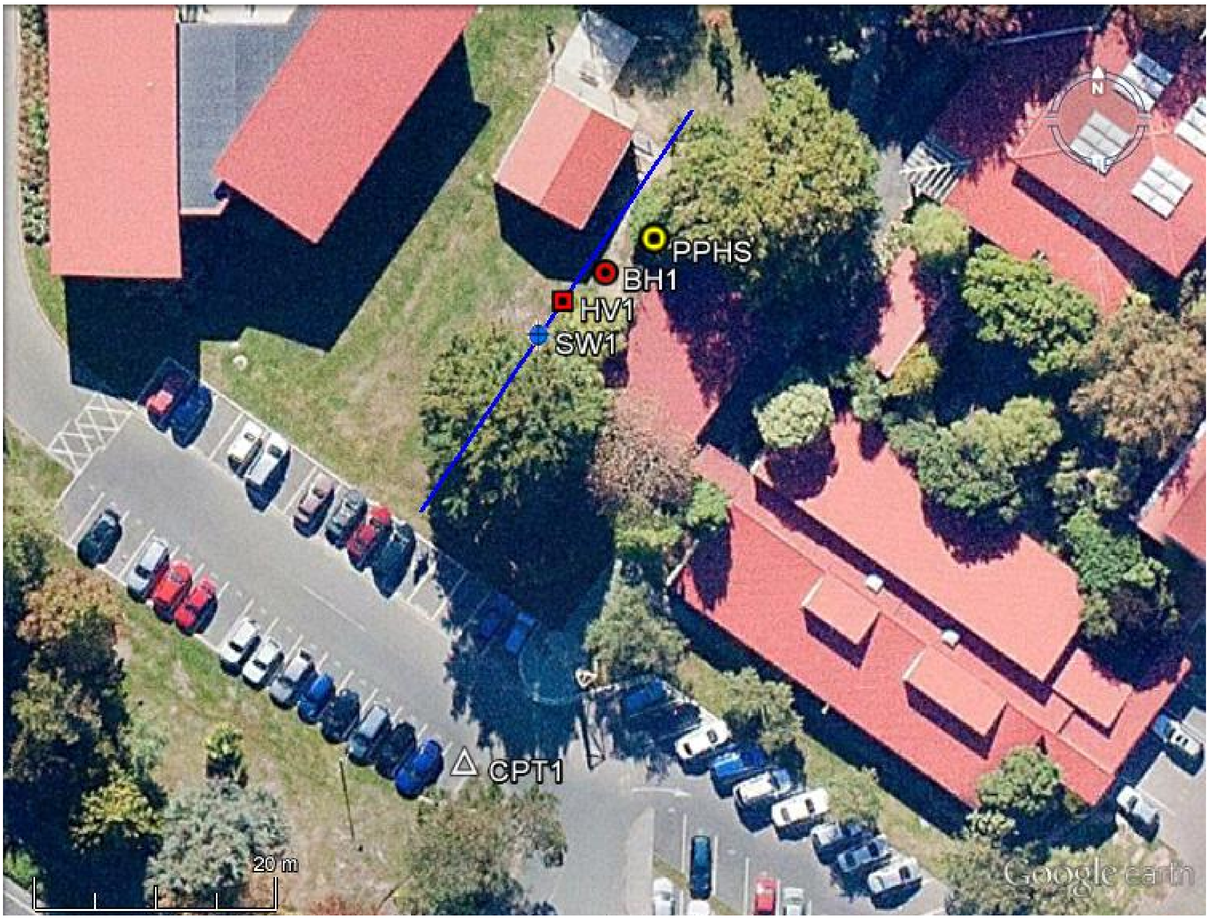


Figure 58 PPHS geotechnical site investigation location plan

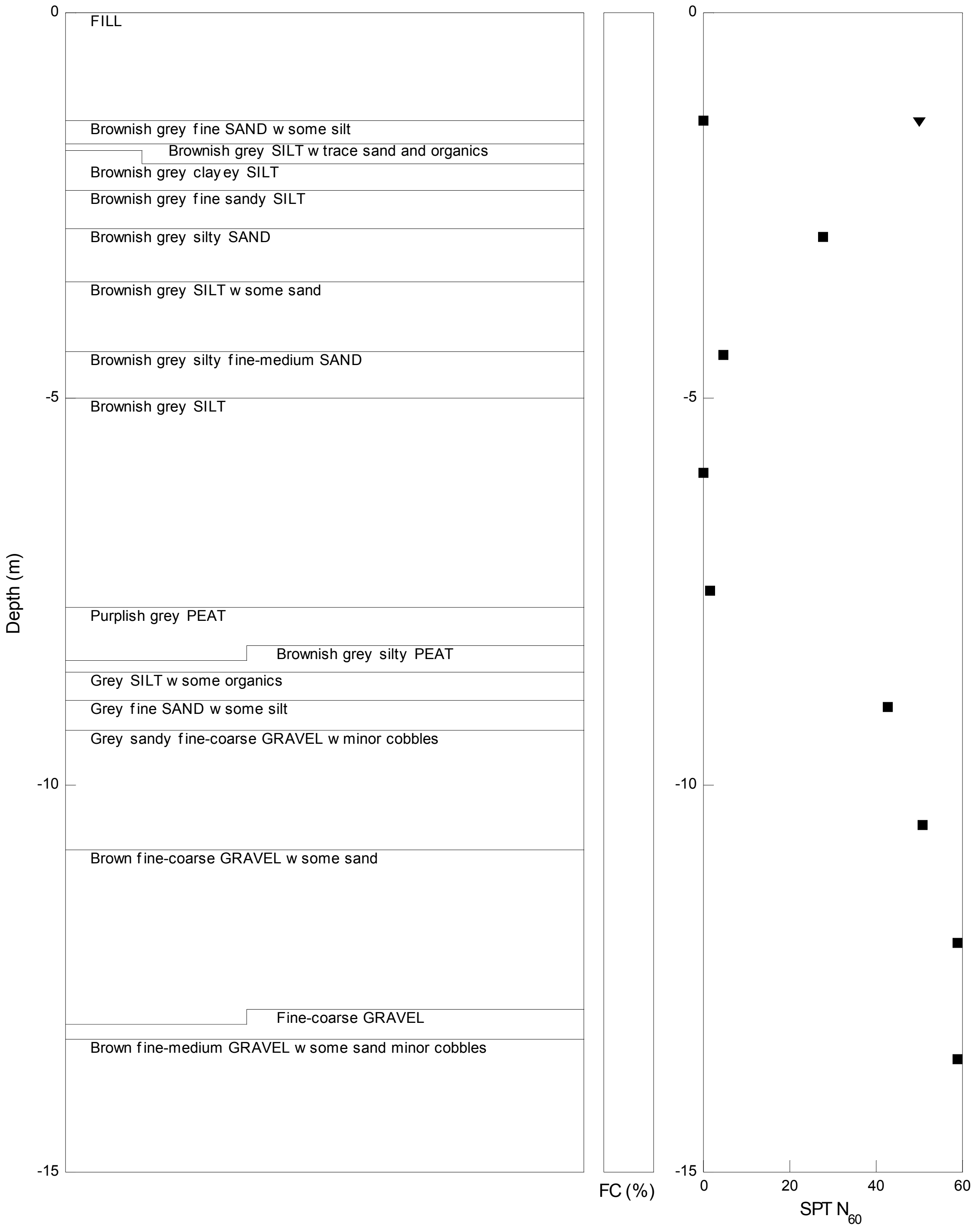
Borehole (PPHS_BH1)

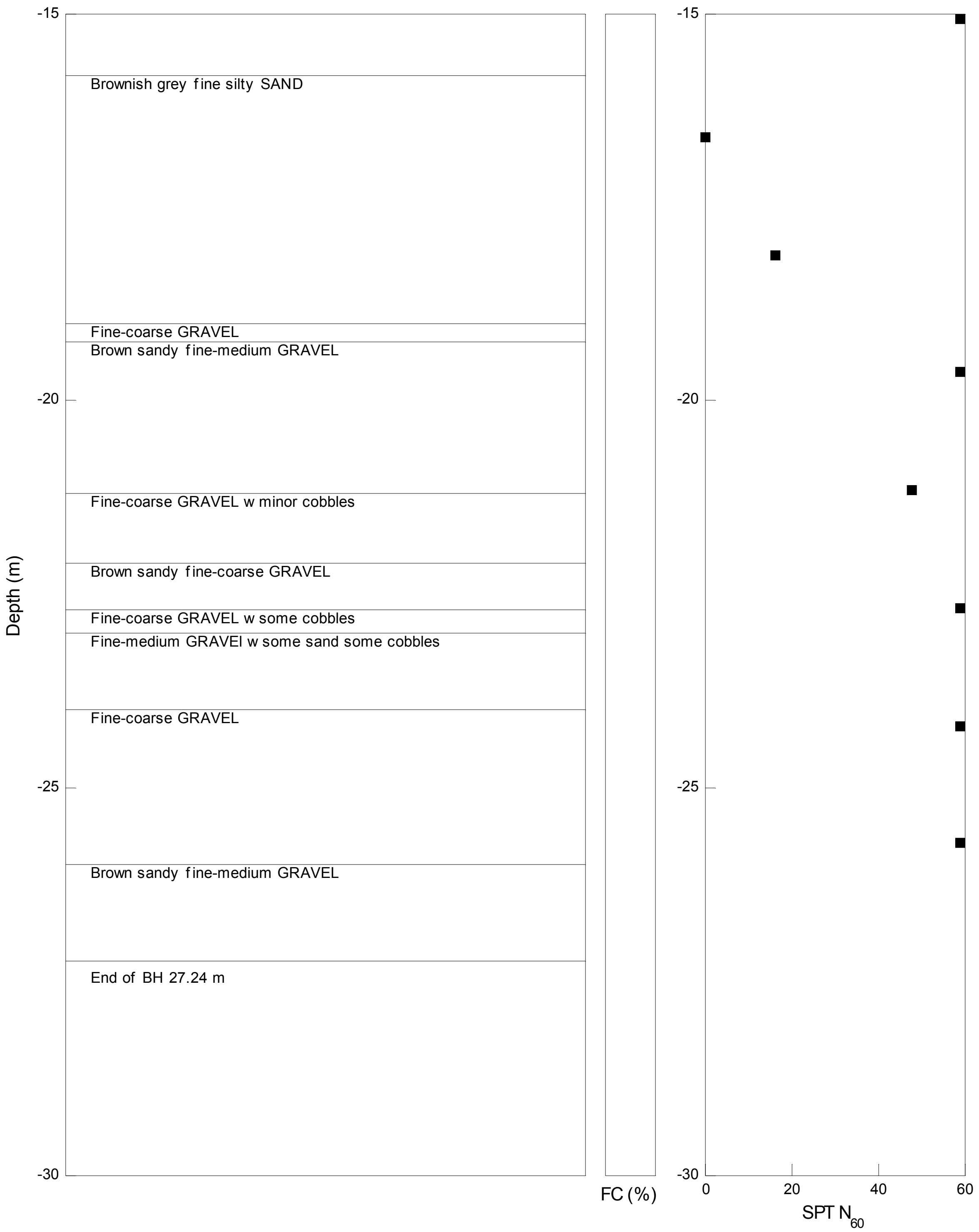
Latitude Longitude (WGS 84): -43.492868 172.606864

Drilling method : Sonic core

Water table depth: 1.5 m

Depth: 27.24 m




Brownish grey fine silty SAND
Fine-coarse GRAVEL
Brown sandy fine-medium GRAVEL
Fine-coarse GRAVEL w minor cobbles
Brown sandy fine-coarse GRAVEL
Fine-coarse GRAVEL w some cobbles
Fine-medium GRAVEl w some sand some cobbles
Fine-coarse GRAVEL
Brown sandy fine-medium GRAVEL
End of BH 27.24 m
Depth (m)
-15
-20
-25
-30
FC (%)
0
20
40
60
SPT N60

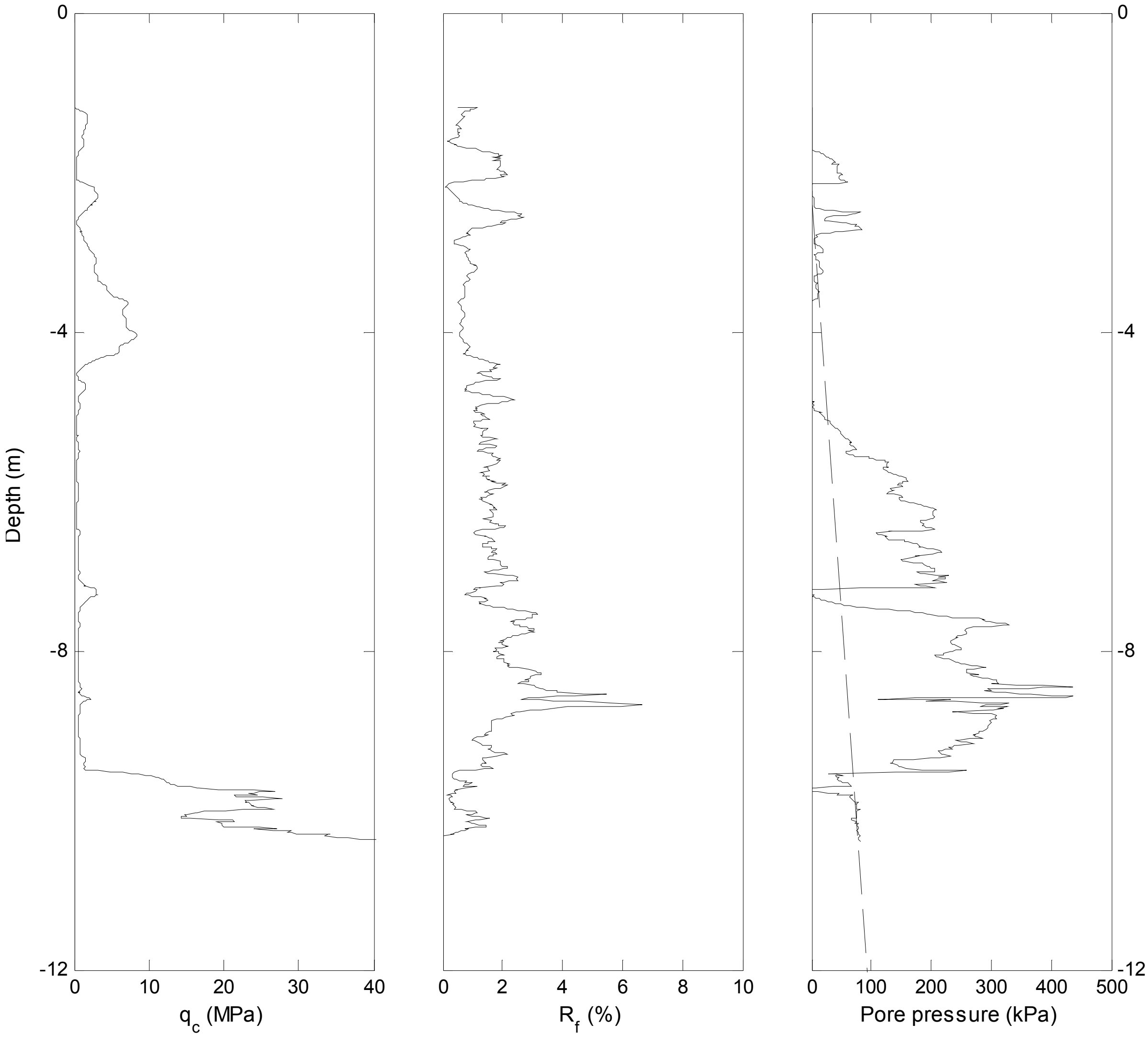
Cone Penetrometer (PPHS_CPT1)

Latitude Longitude (WGS 84): -43.493229 172.606719

Water table depth: 2.4 m

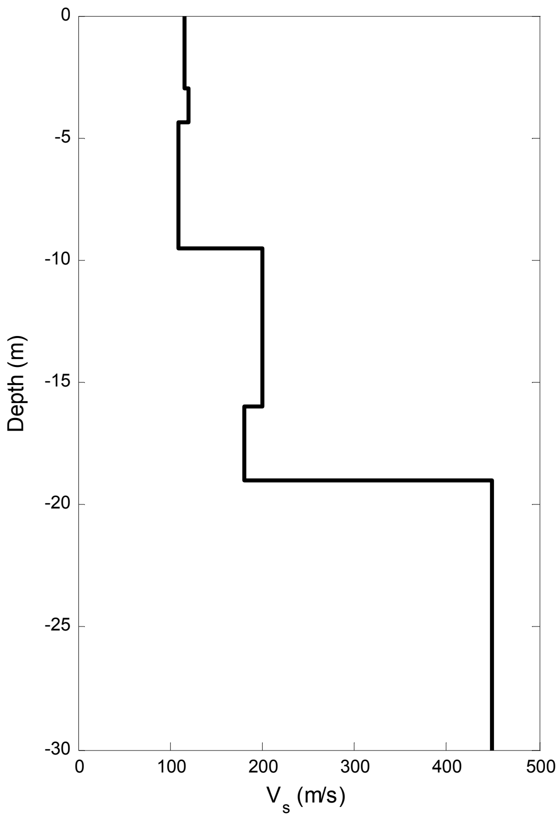
Predrilled: 1.2 m

Depth: 10.38 m



Shear Wave Profile (PPHS_SW1)

Latitude Longitude (WGS 84):	-43.492915 172.606795
Methods:	Active source (MASW, SASW) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.
Source offsets:	5.0 m, 10 m, 20 m
Source:	Minimum of five sledgehammer impacts per offset
Depth:	30 m



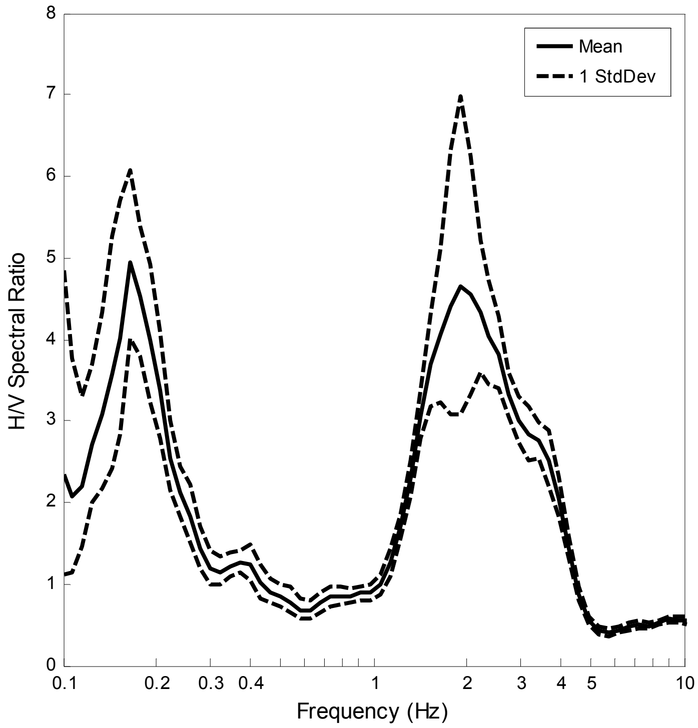
Depth (m)	V_S (m/s)
0.0	115
3.0	120
4.4	110
9.5	200
16.0	180
19.0	450
30.0	

Horizontal-to-vertical (H/V) spectral ratio (PPHS_HV1)

Latitude Longitude (WGS 84): -43.492889 172.606820

Equipment: Nanometrics Trillium compact 120 second broadband seismometer

Record length: 1 hour



C.12 Pages Road Pumping Station (PRPC)

Nearby Geotechnical Site Investigation

Table 22 PRPC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	4	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

Figure 59 PRPC geotechnical site investigation location plan

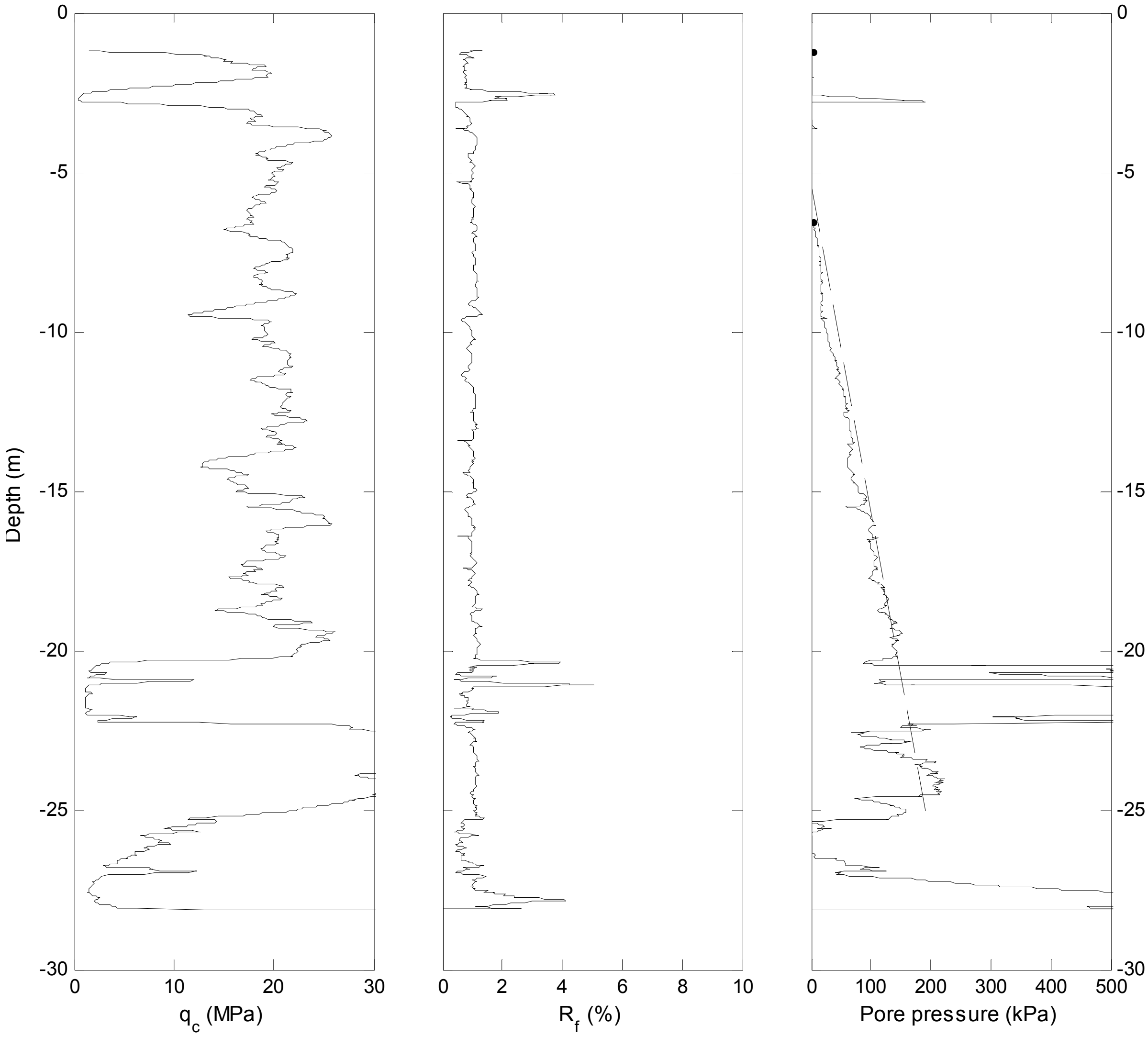
Cone Penetrometer (PRPC_CPT1)

Latitude Longitude (WGS 84): -43.525886 172.682846

Water table depth: 5.5 m

Predrilled: 1.2 m

Depth: 28.16 m



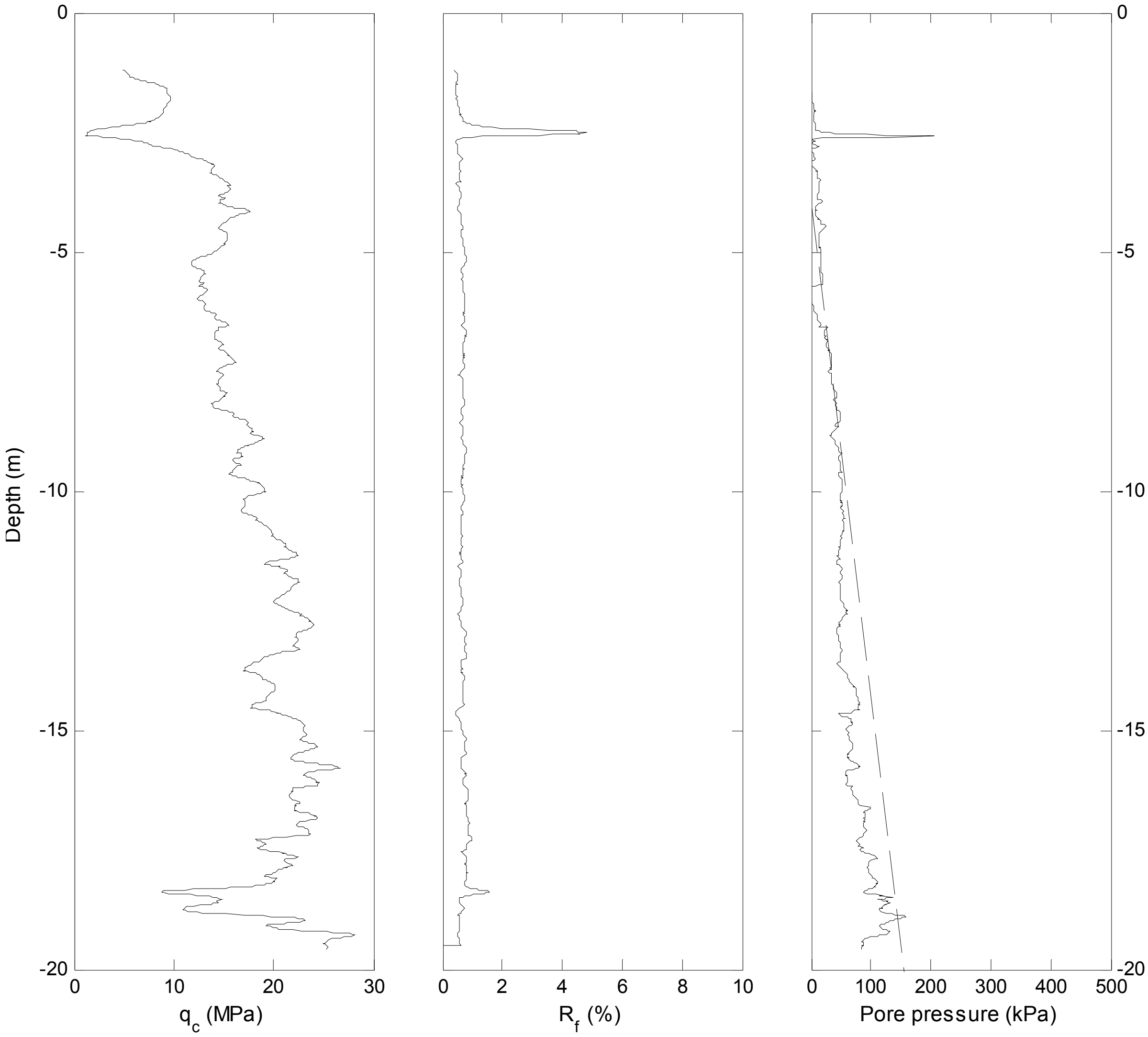
Cone Penetrometer (PRPC_CPT2)

Latitude Longitude (WGS 84): -43.526509 172.682709

Water table depth: 4.1 m

Predrilled: 1.2 m

Depth: 19.56 m



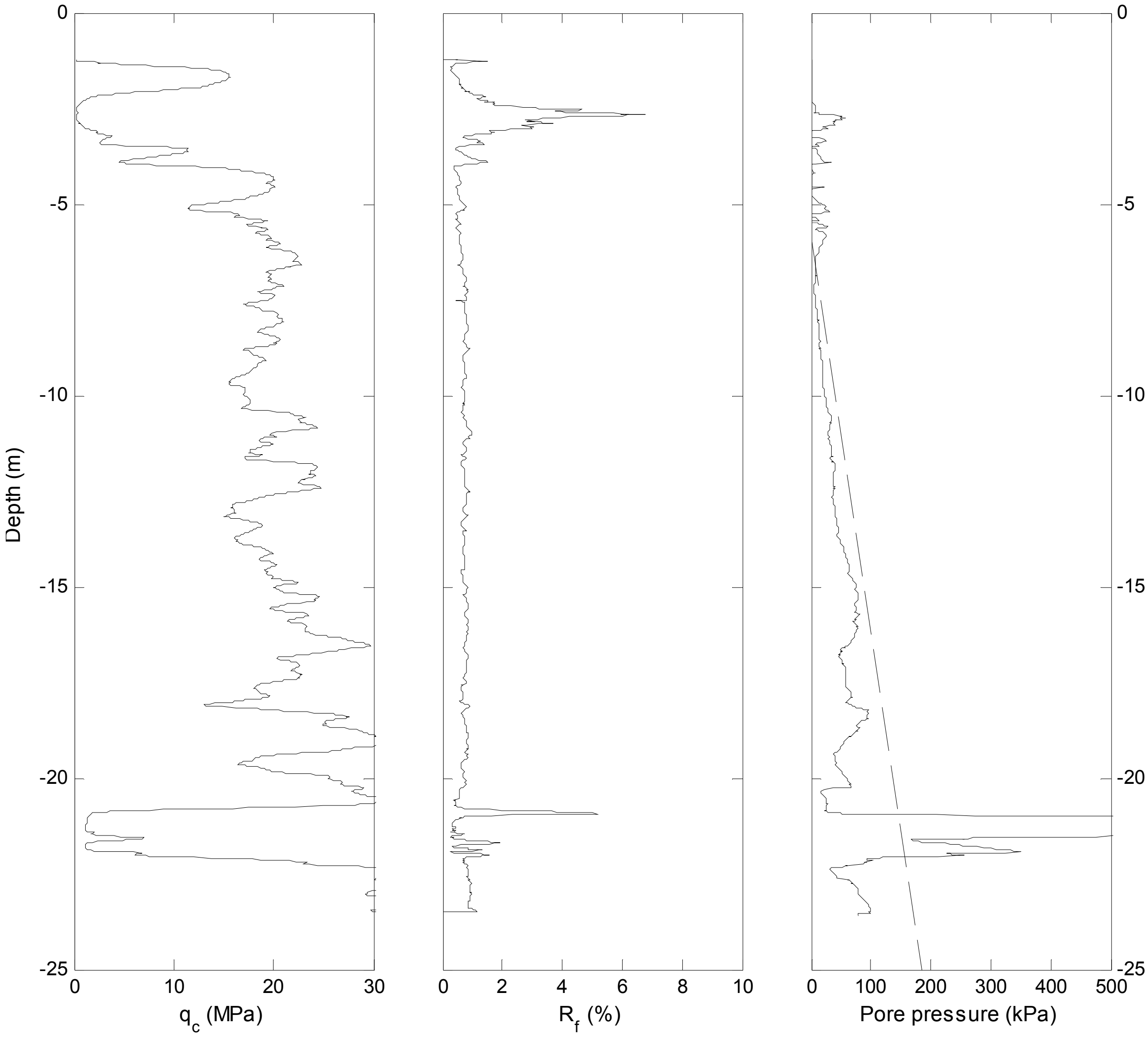
Cone Penetrometer (PRPC_CPT3)

Latitude Longitude (WGS 84): -43.525047 172.682705

Water table depth: 6 m

Predrilled: 1.2 m

Depth: 23.57 m



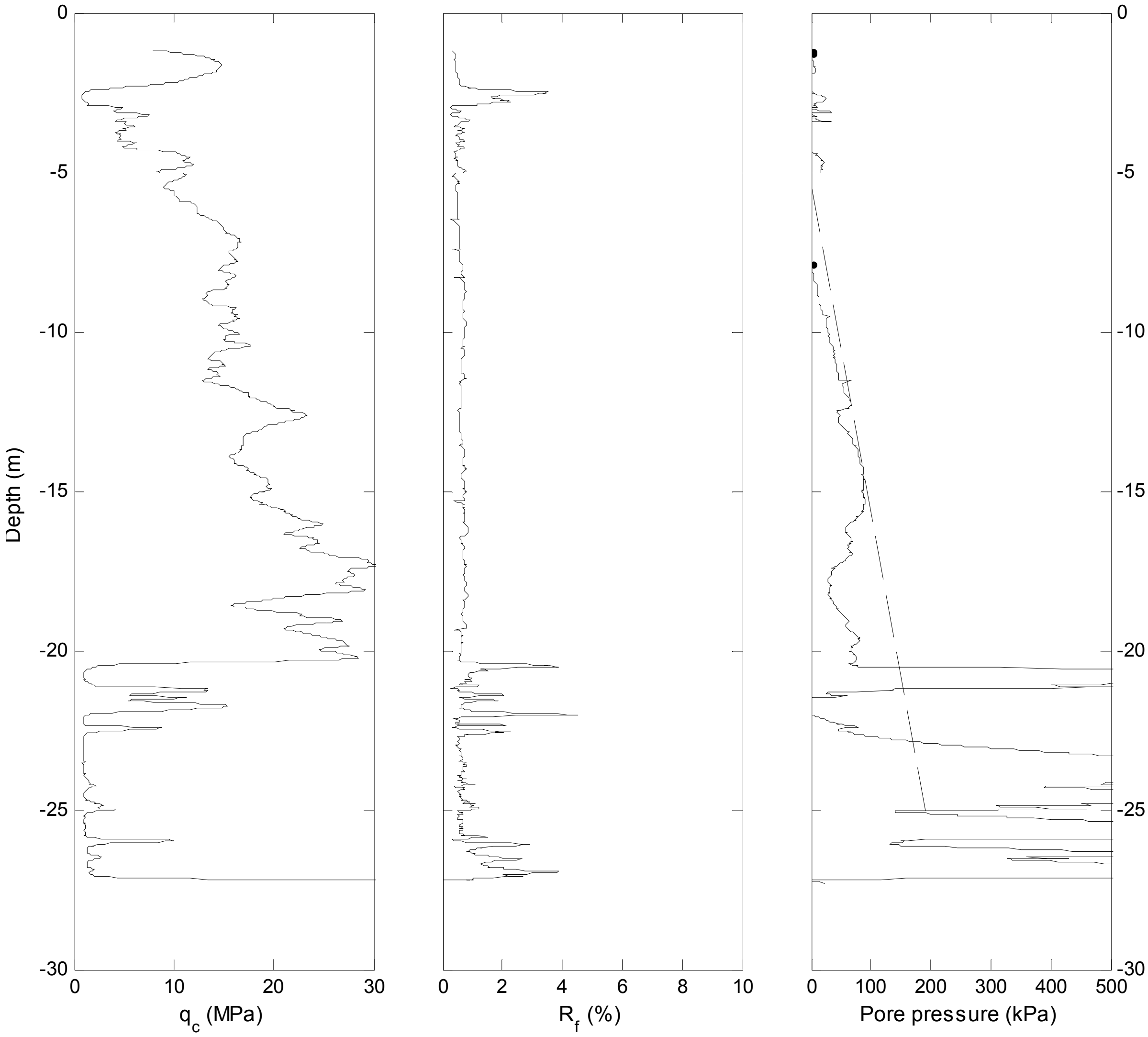
Cone Penetrometer (PRPC_CPT4)

Latitude Longitude (WGS 84): -43.524733 172.681750

Water table depth: 5.5 m

Predrilled: 1.2 m

Depth: 27.28 m



Shear Wave Profile (PRPC_SW1)

Latitude Longitude (WGS 84): -43.525233 172.683350

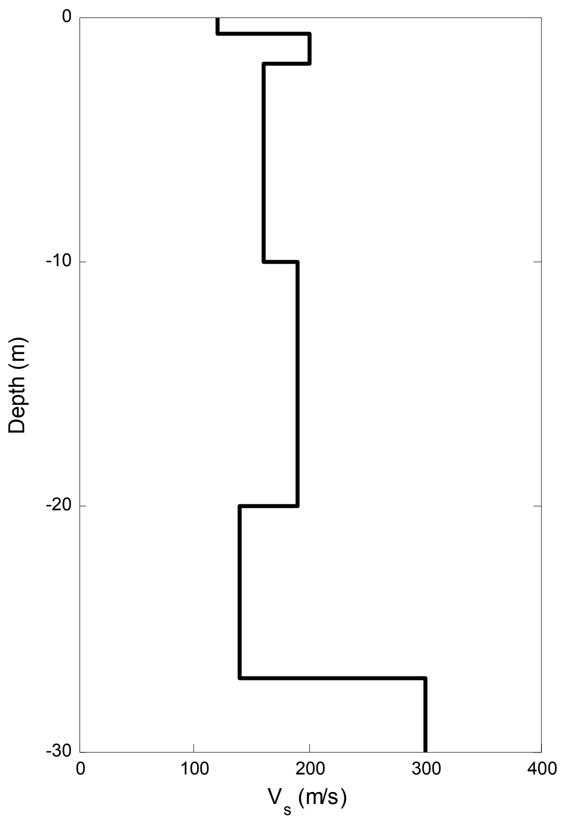
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

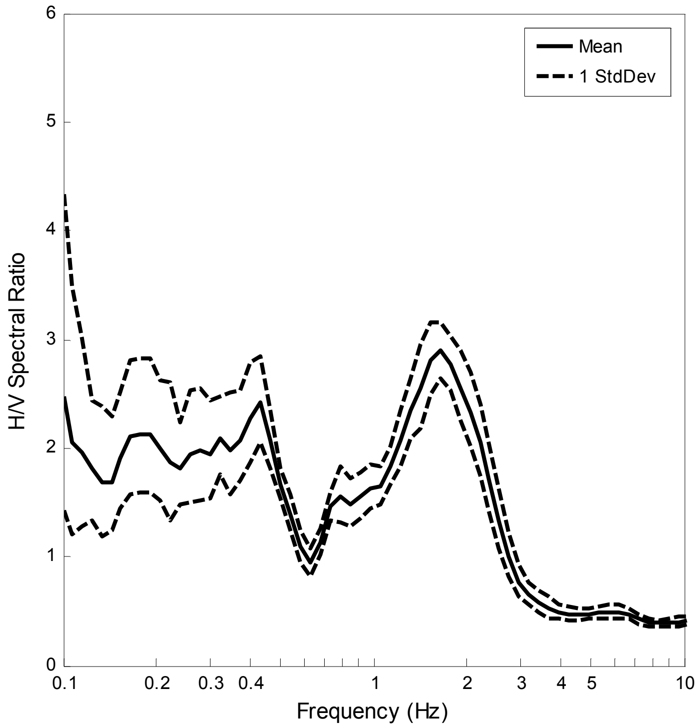
Depth: 30 m



Depth (m)	V_S (m/s)
0.0	121
0.7	200
1.9	160
10.0	190
20.0	140
27.0	300
30.0	

Horizontal-to-vertical (H/V) spectral ratio (PRPC_HV1)

Latitude Longitude (WGS 84):	-43.525259 172.683164
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.13 Christchurch Resthaven (REHS)

Nearby Geotechnical Site Investigations

Table 23 REHS geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	2	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

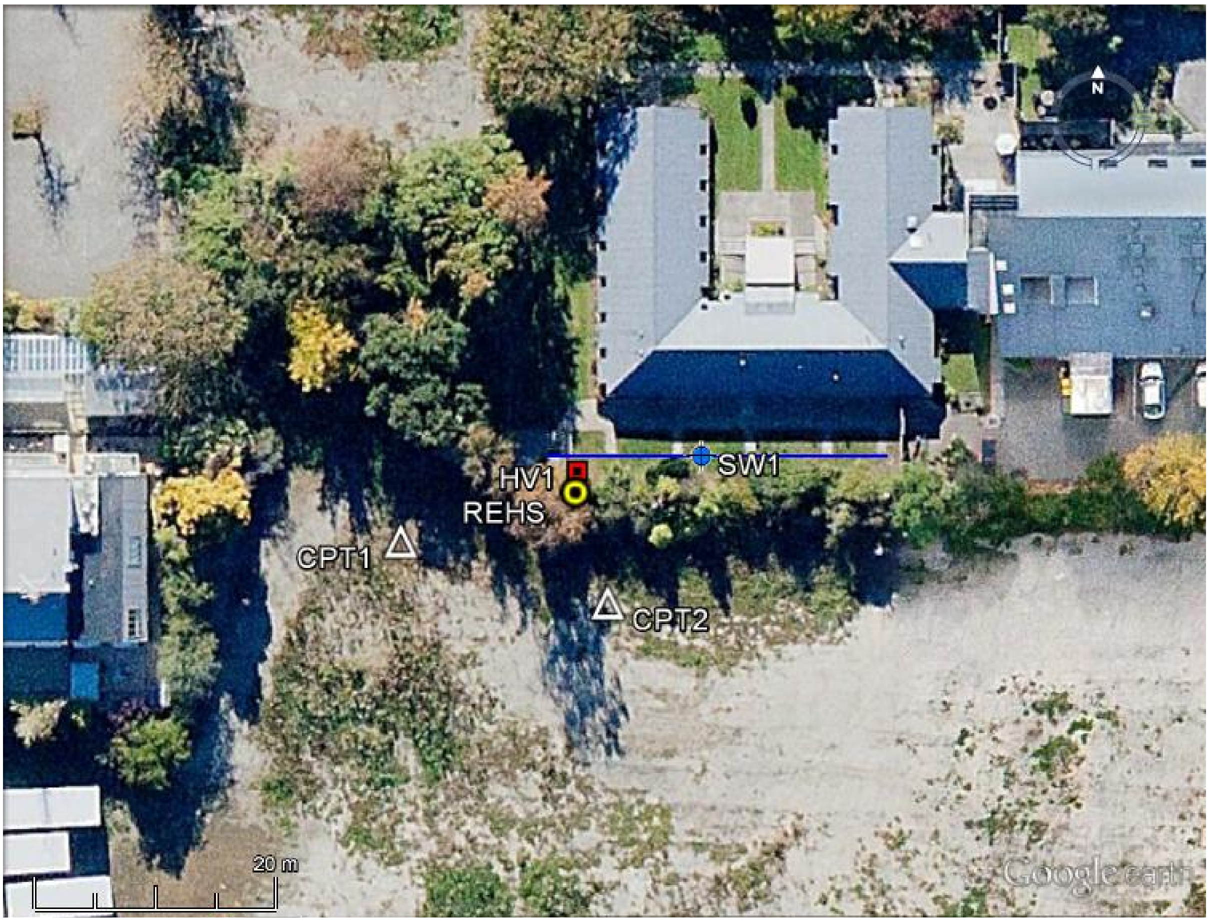
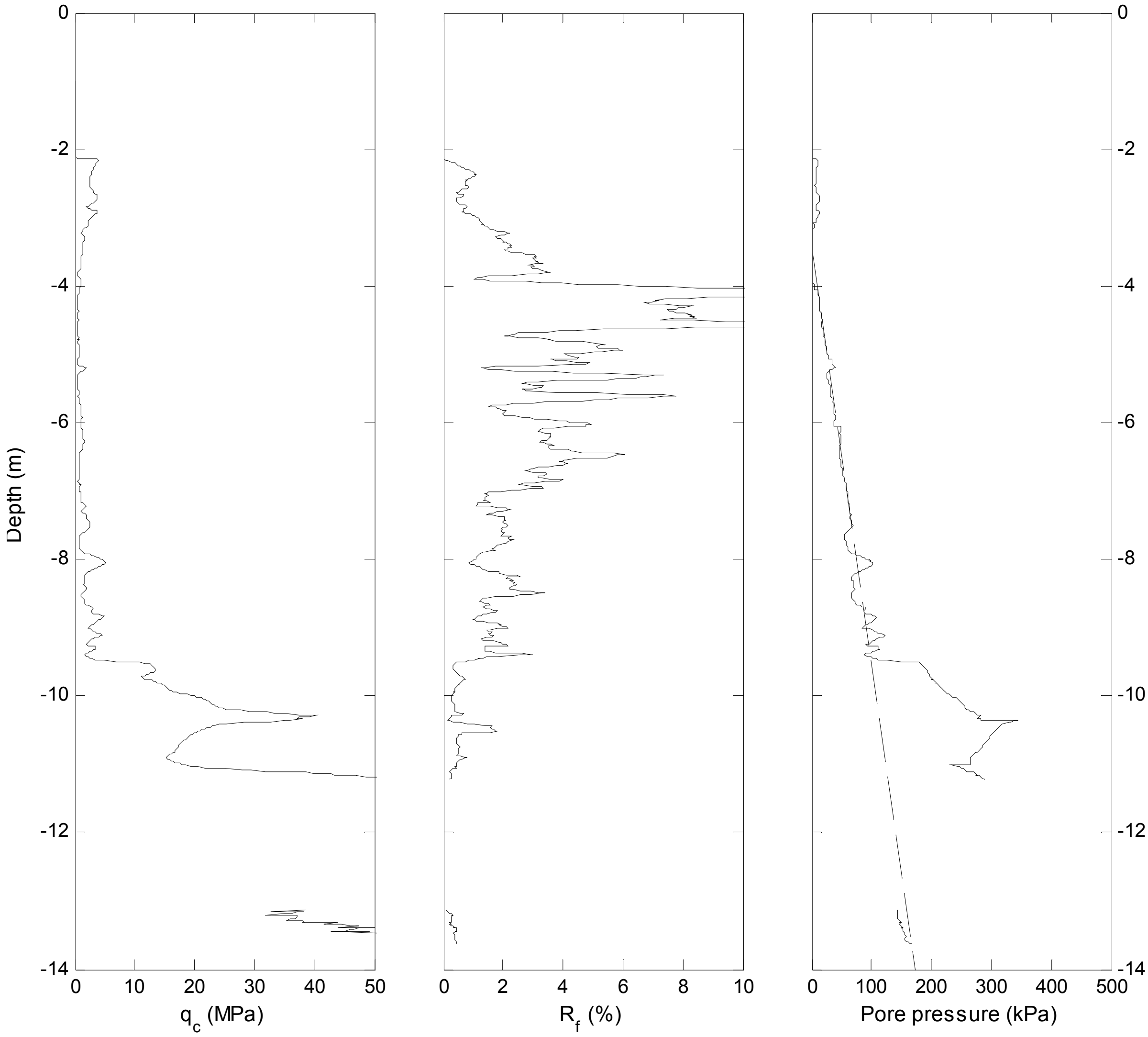


Figure 60 REHS geotechnical site investigation location plan

Cone Penetrometer (REHS_CPT1)

Latitude Longitude (WGS 84):	-43.521983 172.634971
Water table depth:	3.5 m
Predrilled:	2 m
Depth:	13.63 m



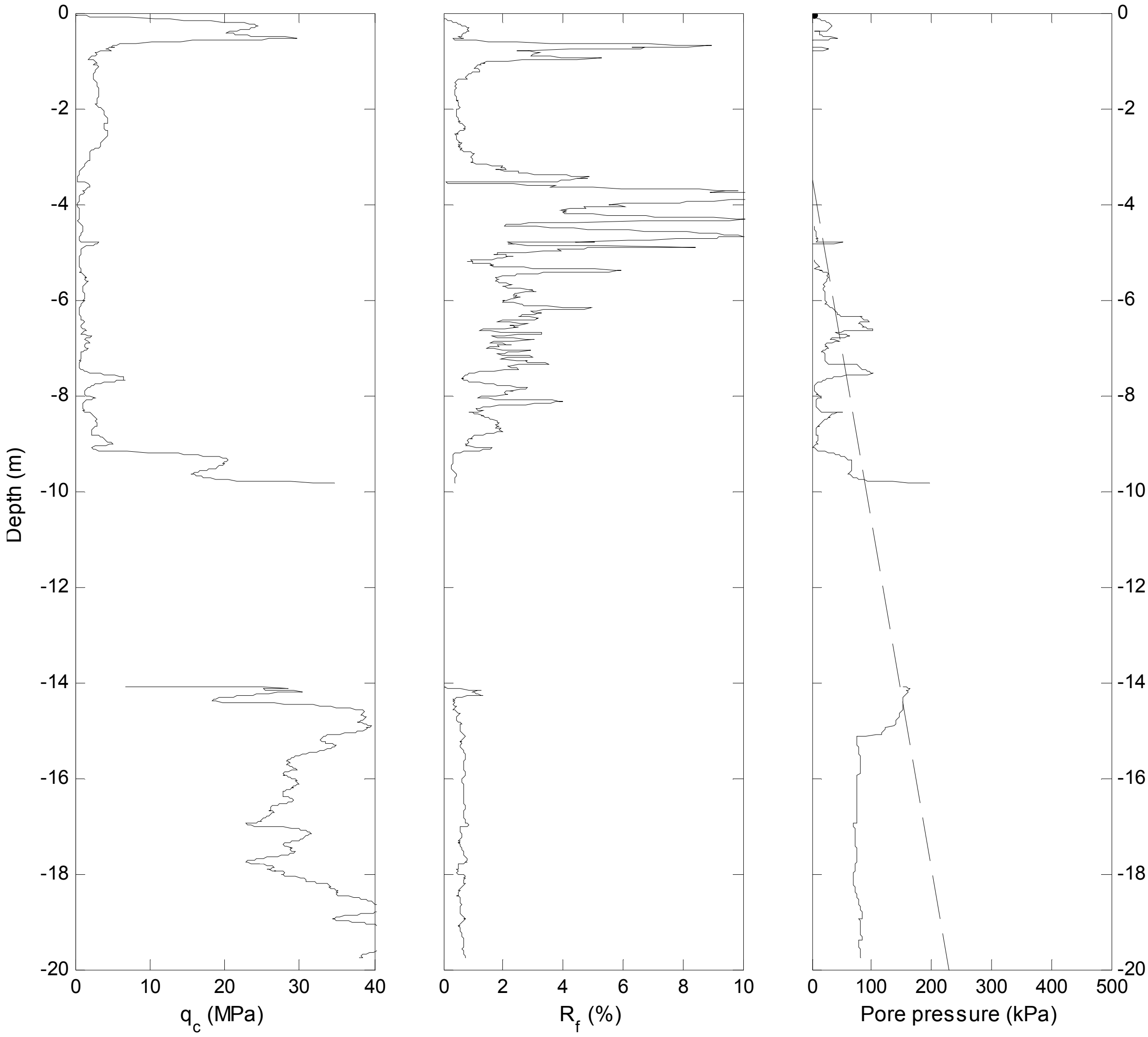
Cone Penetrometer (REHS_CPT2)

Latitude Longitude (WGS 84): -43.522028 172.635181

Water table depth: 3.5 m

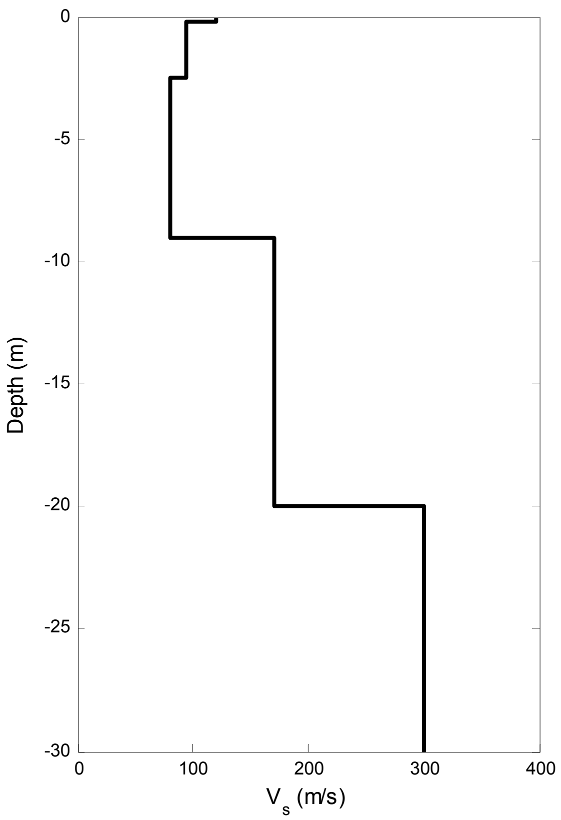
Predrilled: 0 m

Depth: 19.76 m



Shear Wave Profile (REHS_SW1)

Latitude Longitude (WGS 84):	-43.521917 172.635150
Methods:	Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 0.9 m spacing. Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.
MASW Source offsets:	4.6 m, 9.1m, 18.3 m
Source:	Minimum of five sledgehammer impacts per offset
Depth:	30 m



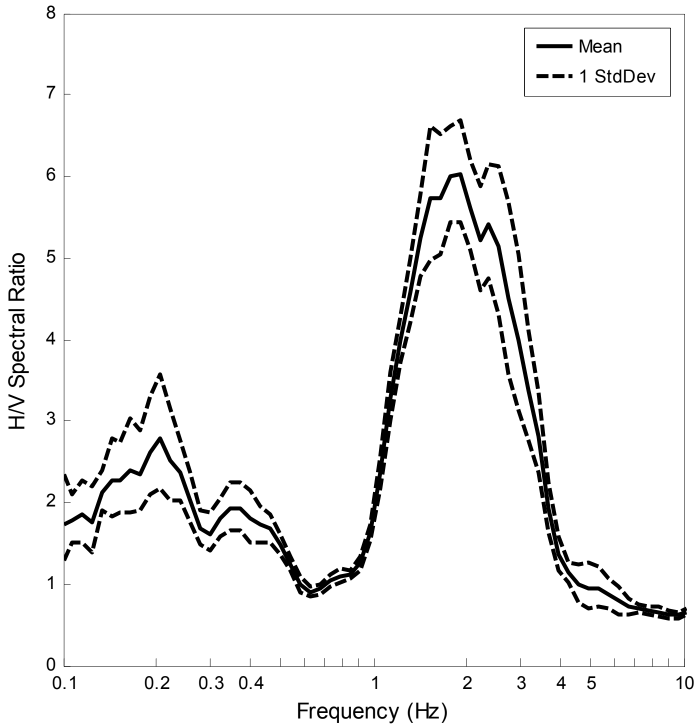
Depth (m)	V_S (m/s)
0.0	120
0.2	95
2.5	80
9.0	170
20.0	300
30.0	

Horizontal-to-vertical (H/V) spectral ratio (REHS_HV1)

Latitude Longitude (WGS 84): -43.521930 172.635151

Equipment: Nanometrics Trillium compact 120 second broadband seismometer

Record length: 2 hours



Surrounding Geotechnical Site Investigations

Table 24 REHS surrounding geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	5	
Borehole/SPT (BH)	2	
V_s – surface wave (SW)	0	
H/V Spectral Ratio (HV)	0	

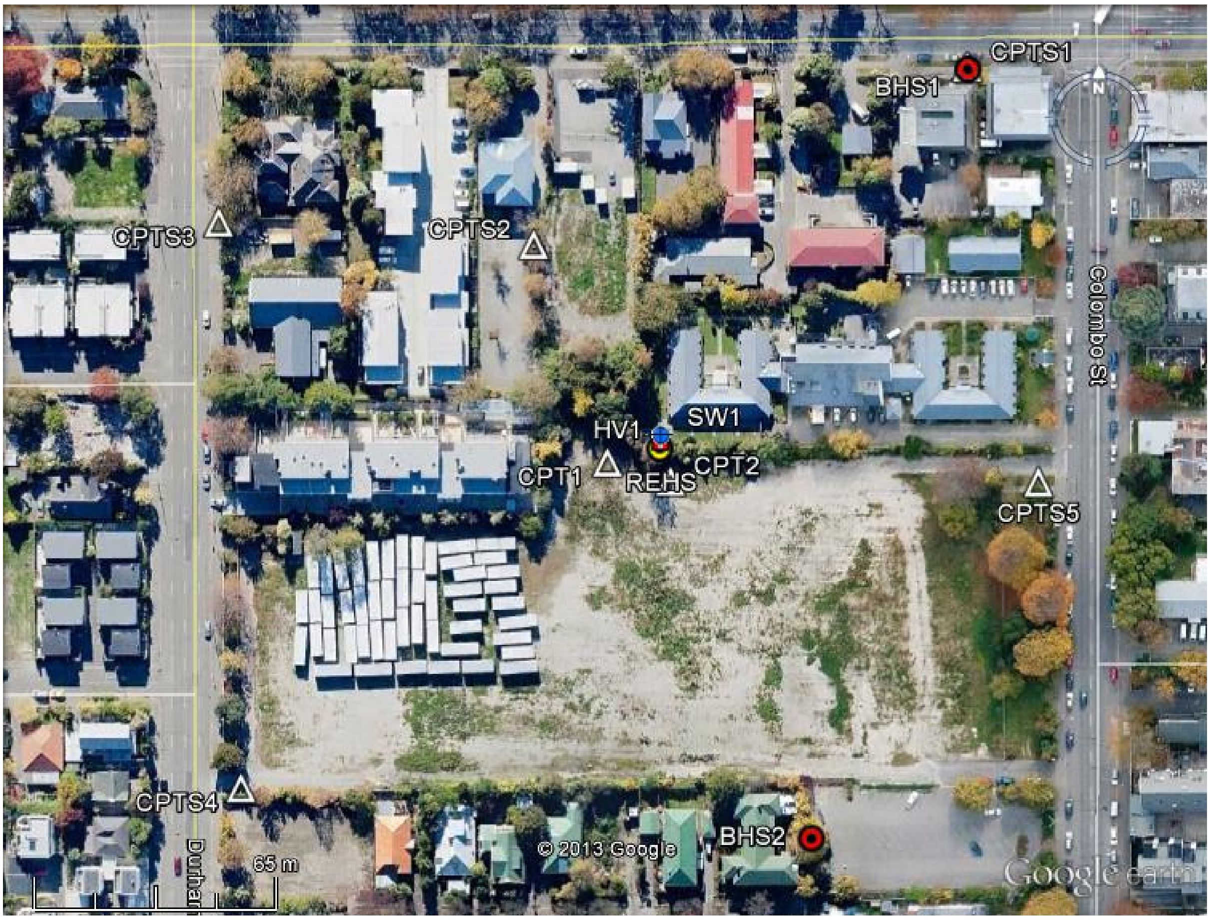


Figure 61 REHS surrounding geotechnical site investigation location plan

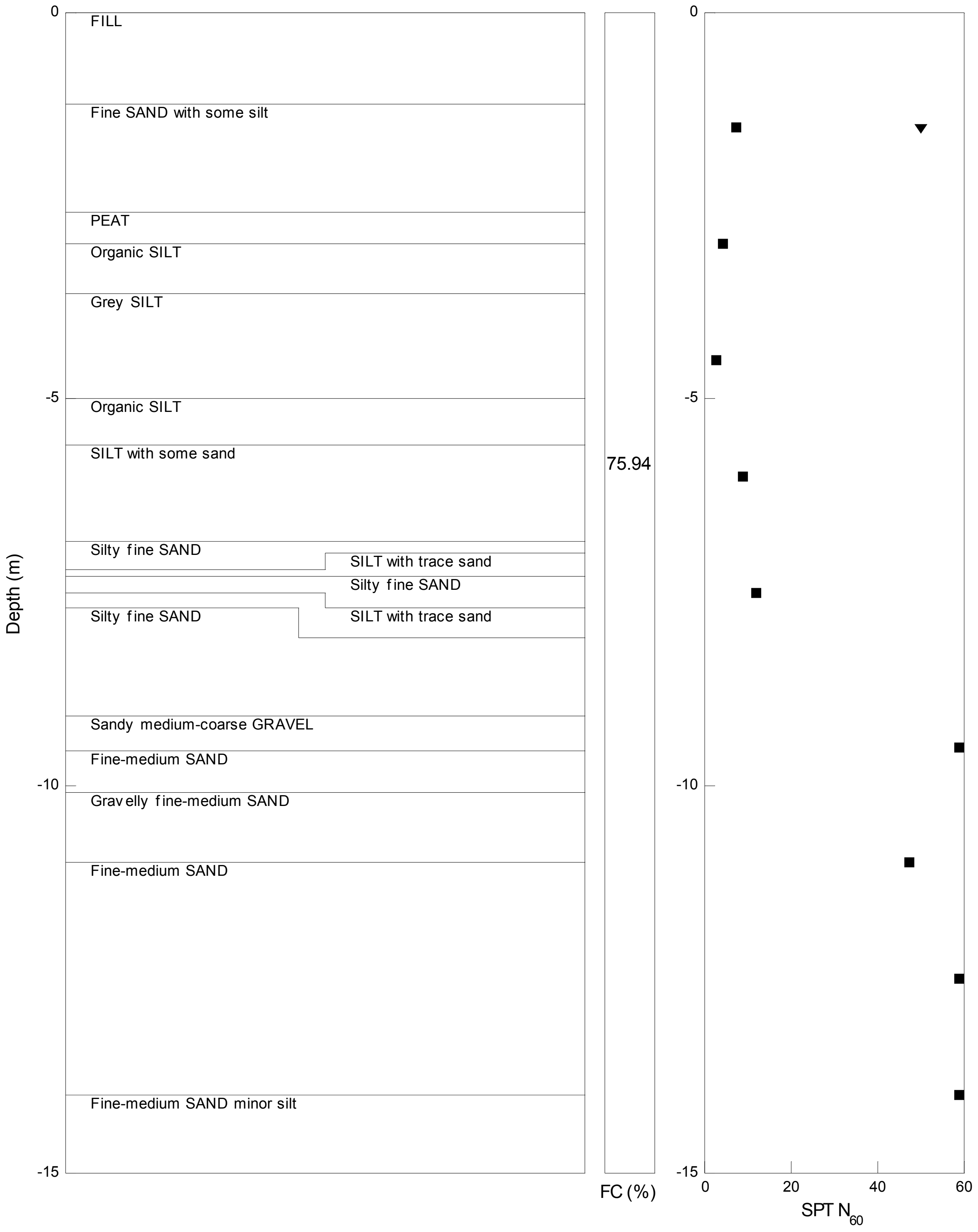
Borehole (REHS_BHS1)

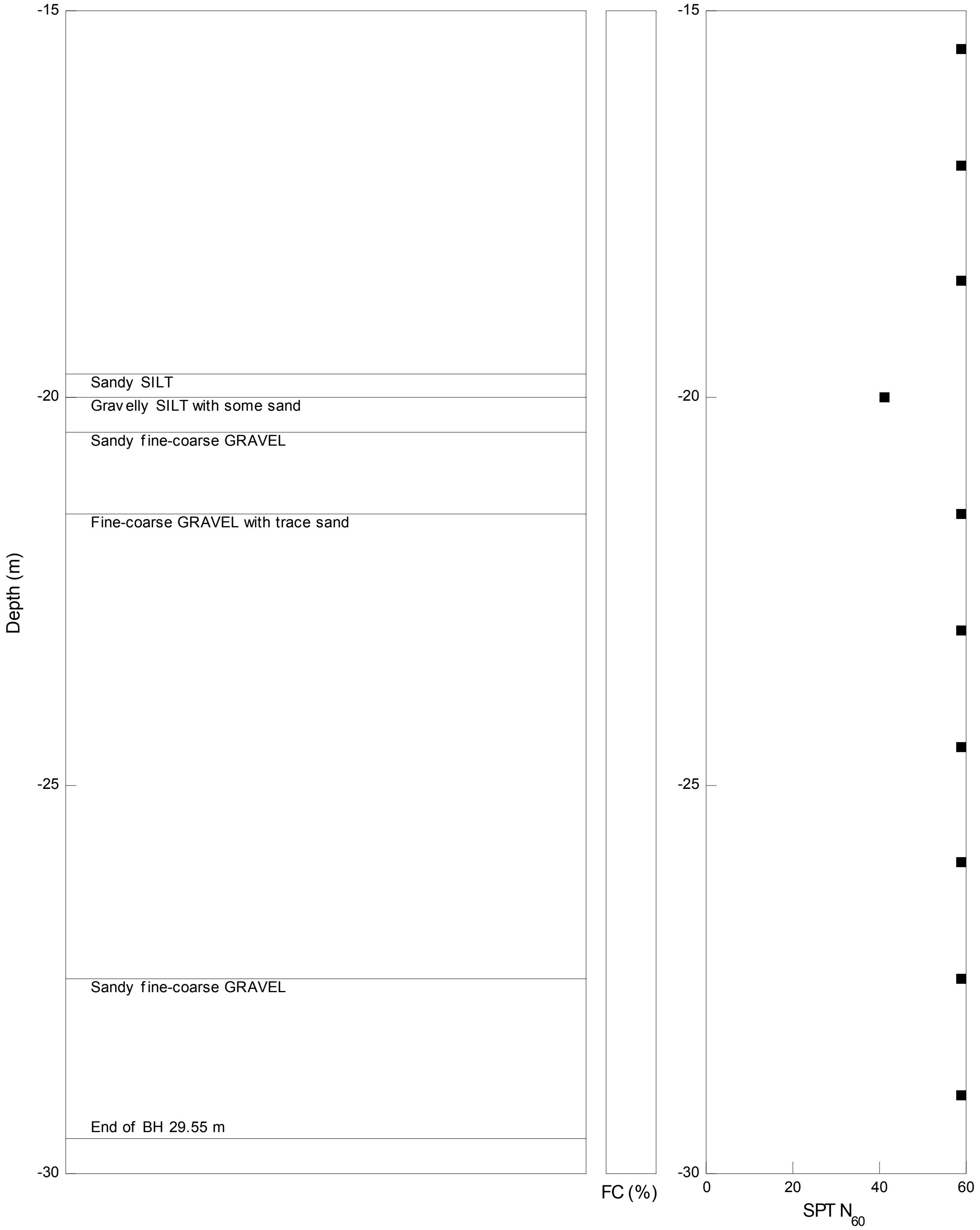
Latitude Longitude (WGS 84): -43.521027 172.636179

Drilling method : Mud Rotary

Water table depth: 1.6 m

Depth: 29.55 m




-15
-20
-25
-30
Depth (m)
Sandy SILT
Gravelly SILT with some sand
Sandy fine-coarse GRAVEL
Fine-coarse GRAVEL with trace sand
Sandy fine-coarse GRAVEL
End of BH 29.55 m
FC (%)
0
20
40
60
SPT N_{60}

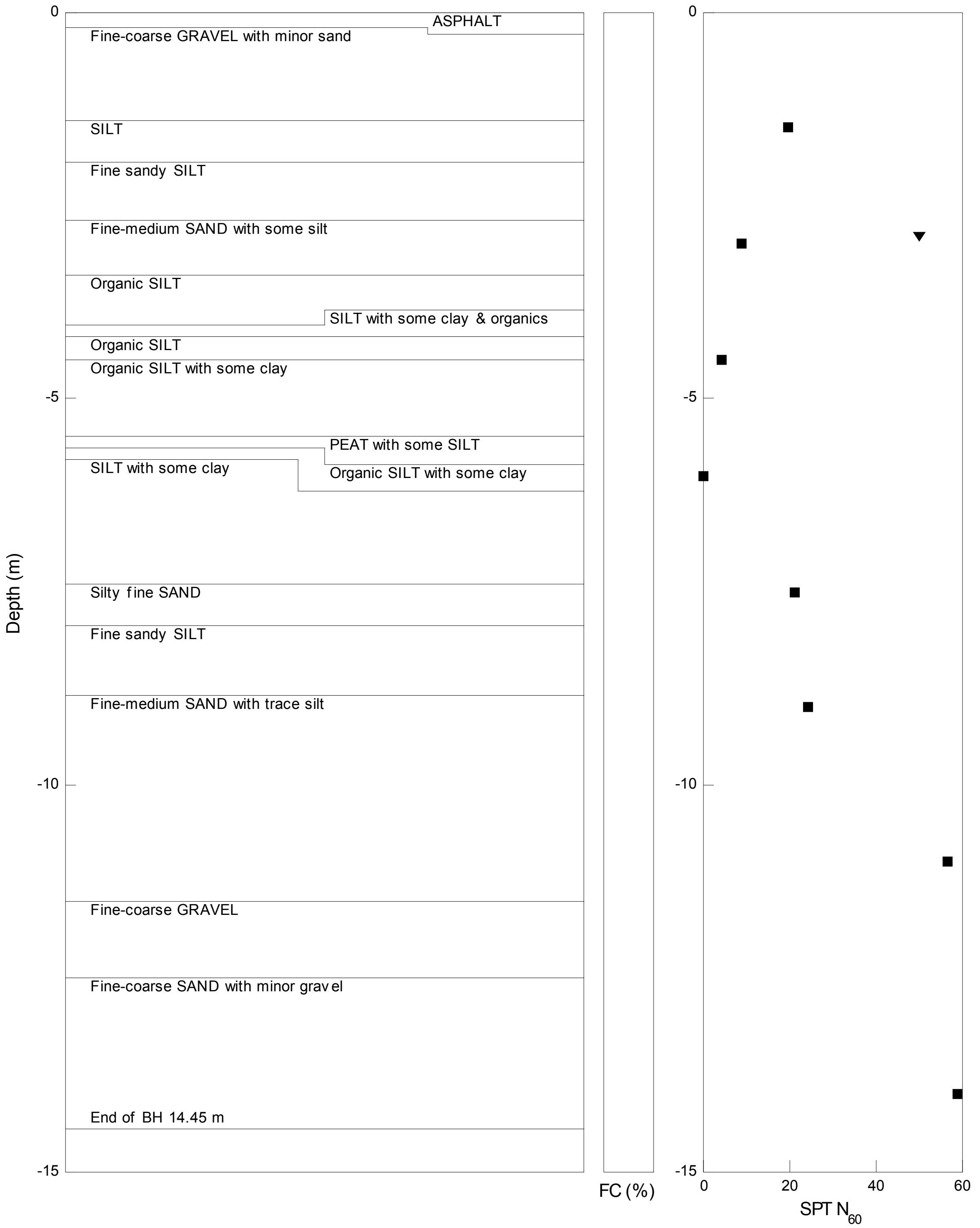
Borehole (REHS_BHS2)

Latitude Longitude (WGS 84): -43.522889 172.635657

Drilling method : Mud Rotary

Water table depth: 3 m

Depth: 14.45 m



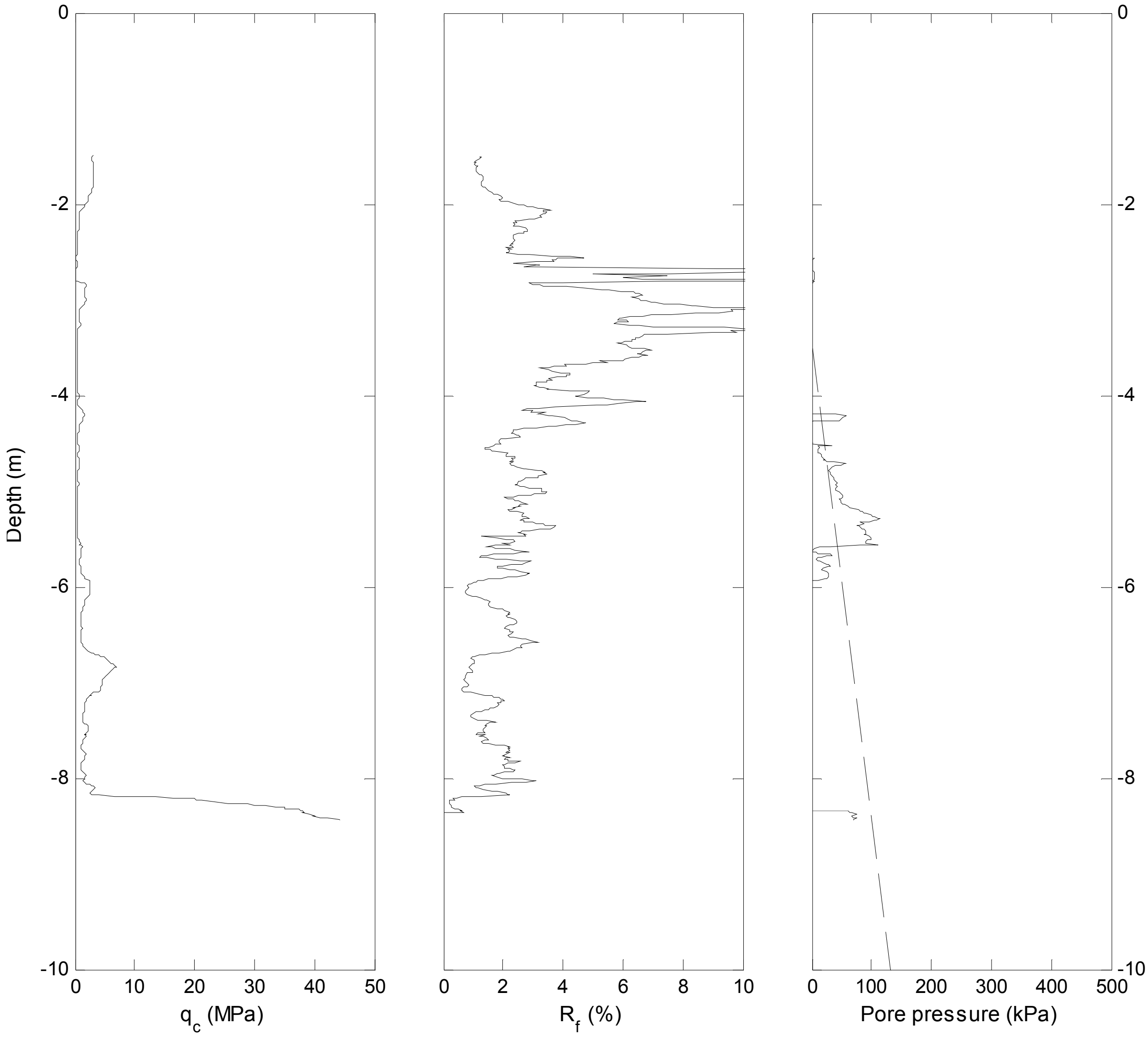
Cone Penetrometer (REHS_CPTS1)

Latitude Longitude (WGS 84): -43.521026 172.636172

Water table depth: 3.5 m

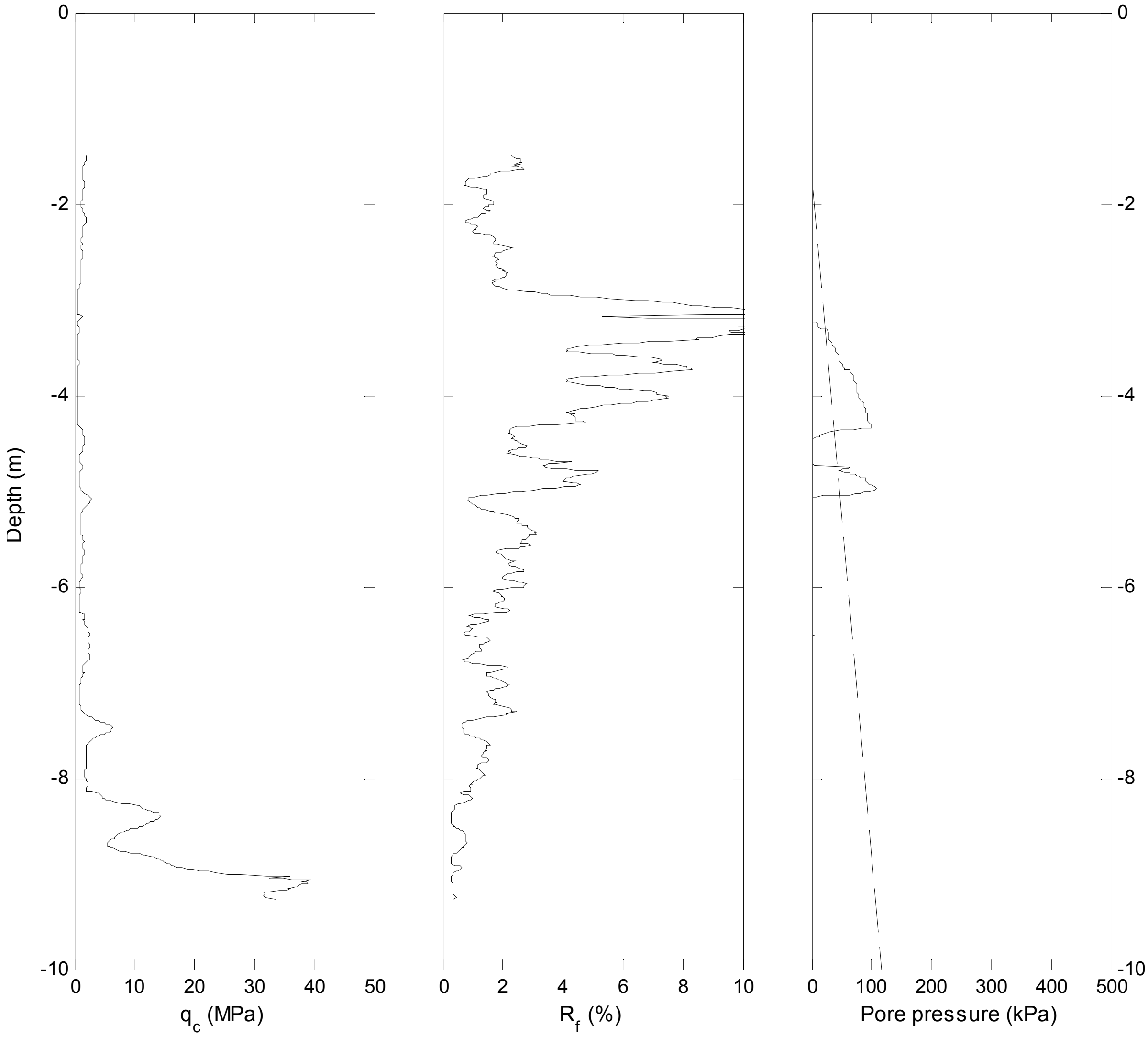
Predrilled: 1.5 m

Depth: 8.43 m



Cone Penetrometer (REHS_CPTS2)

Latitude Longitude (WGS 84):	-43.521456 172.634725
Water table depth:	1.8 m
Predrilled:	1.5 m
Depth:	9.26 m



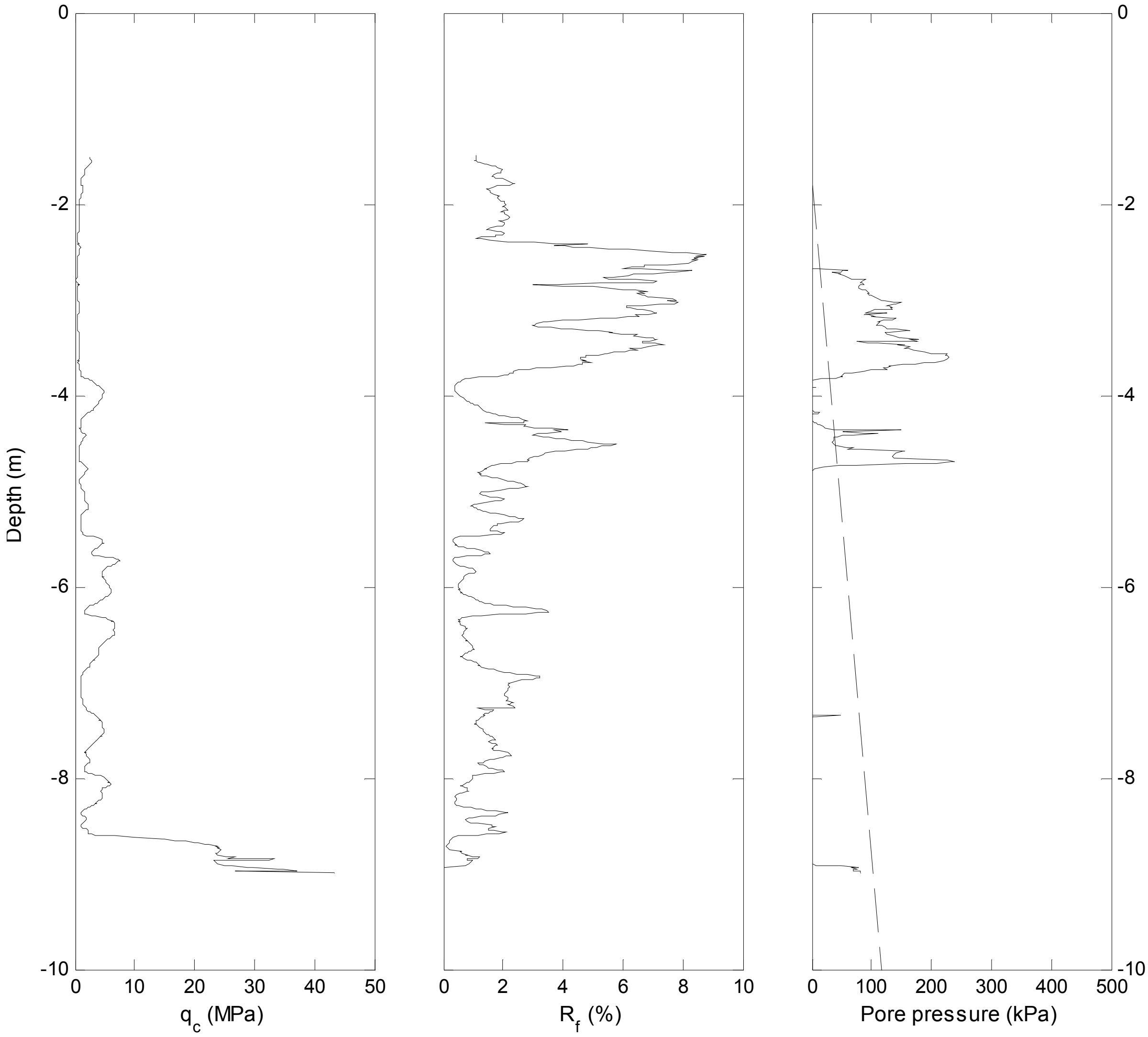
Cone Penetrometer (REHS_CPTS3)

Latitude Longitude (WGS 84): -43.521402 172.633673

Water table depth: 2.5 m

Predrilled: 1.5 m

Depth: 8.99 m



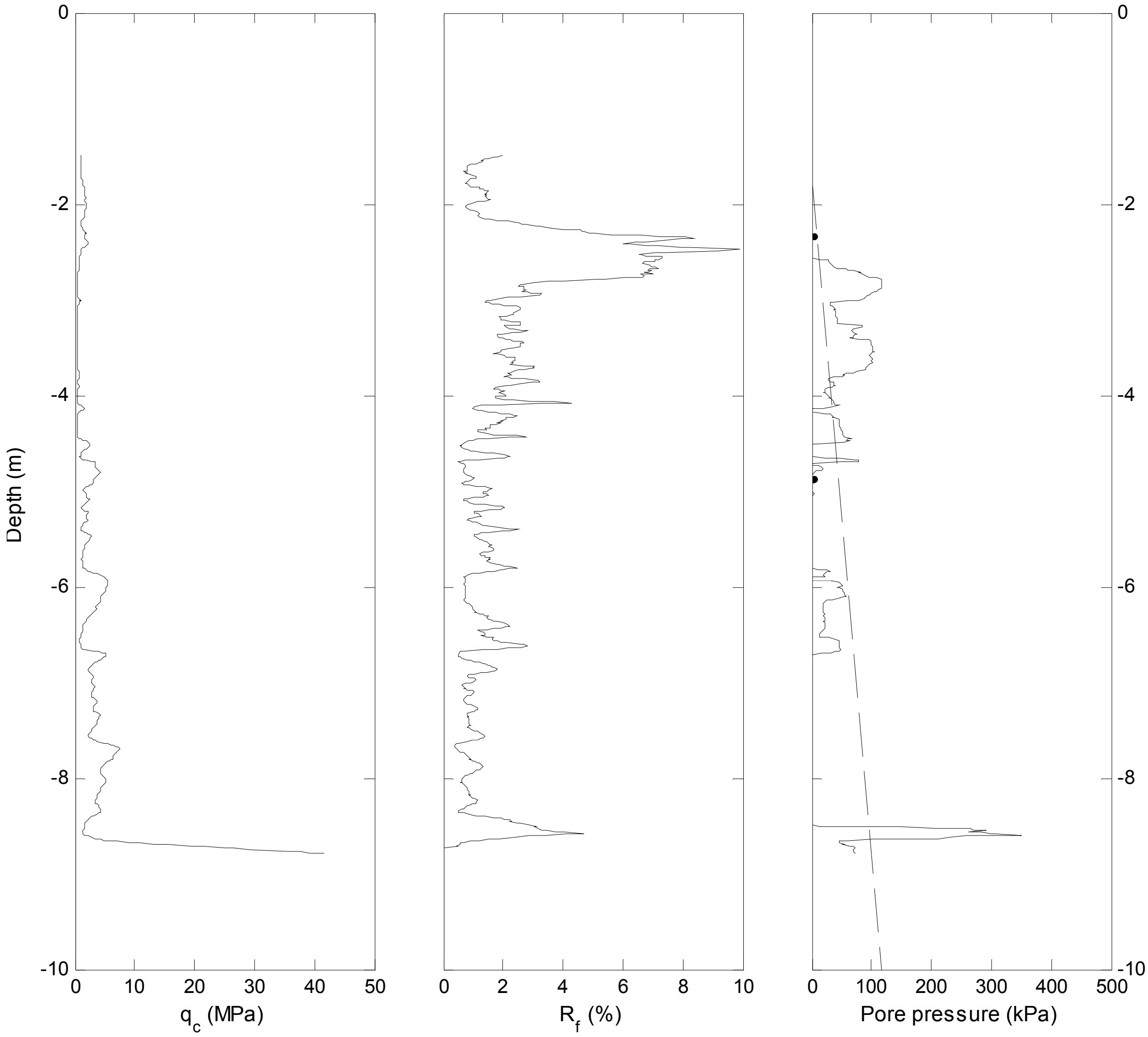
Cone Penetrometer (REHS_CPTS4)

Latitude Longitude (WGS 84): -43.522771 172.633747

Water table depth: 2.0 m

Predrilled: 1.5 m

Depth: 8.79 m



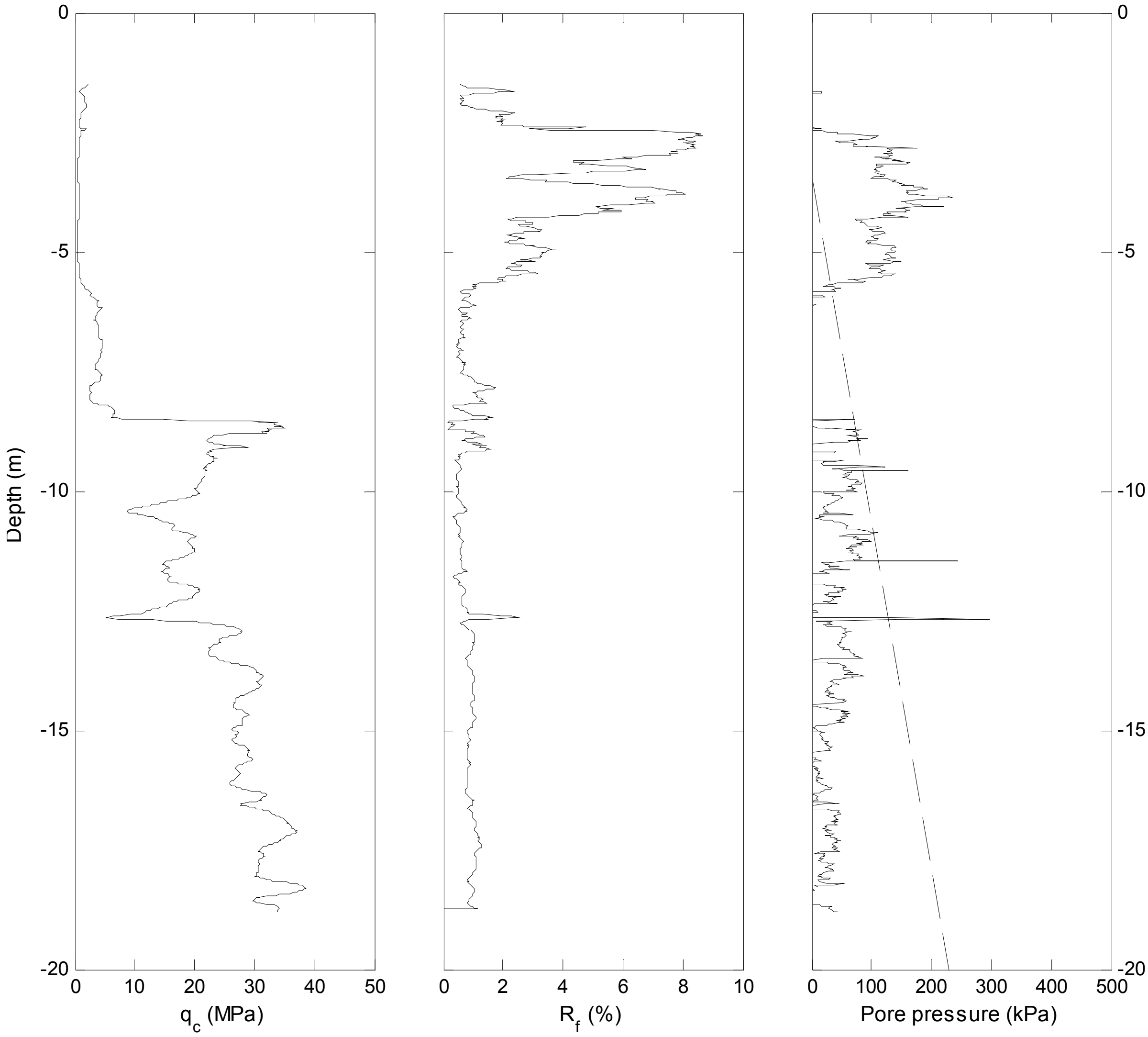
Cone Penetrometer (REHS_CPTS5)

Latitude Longitude (WGS 84): -43.522031 172.636410

Water table depth: 2.0 m

Predrilled: 1.5 m

Depth: 18.80 m



C.14 Riccarton High School (RHSC)

Nearby Geotechnical Site Investigation

Table 25 RHSC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	0	Gravelly site
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	Deep V_s profiling at site
H/V (HV)	1	

Figure 62 RHSC geotechnical site investigation location plan

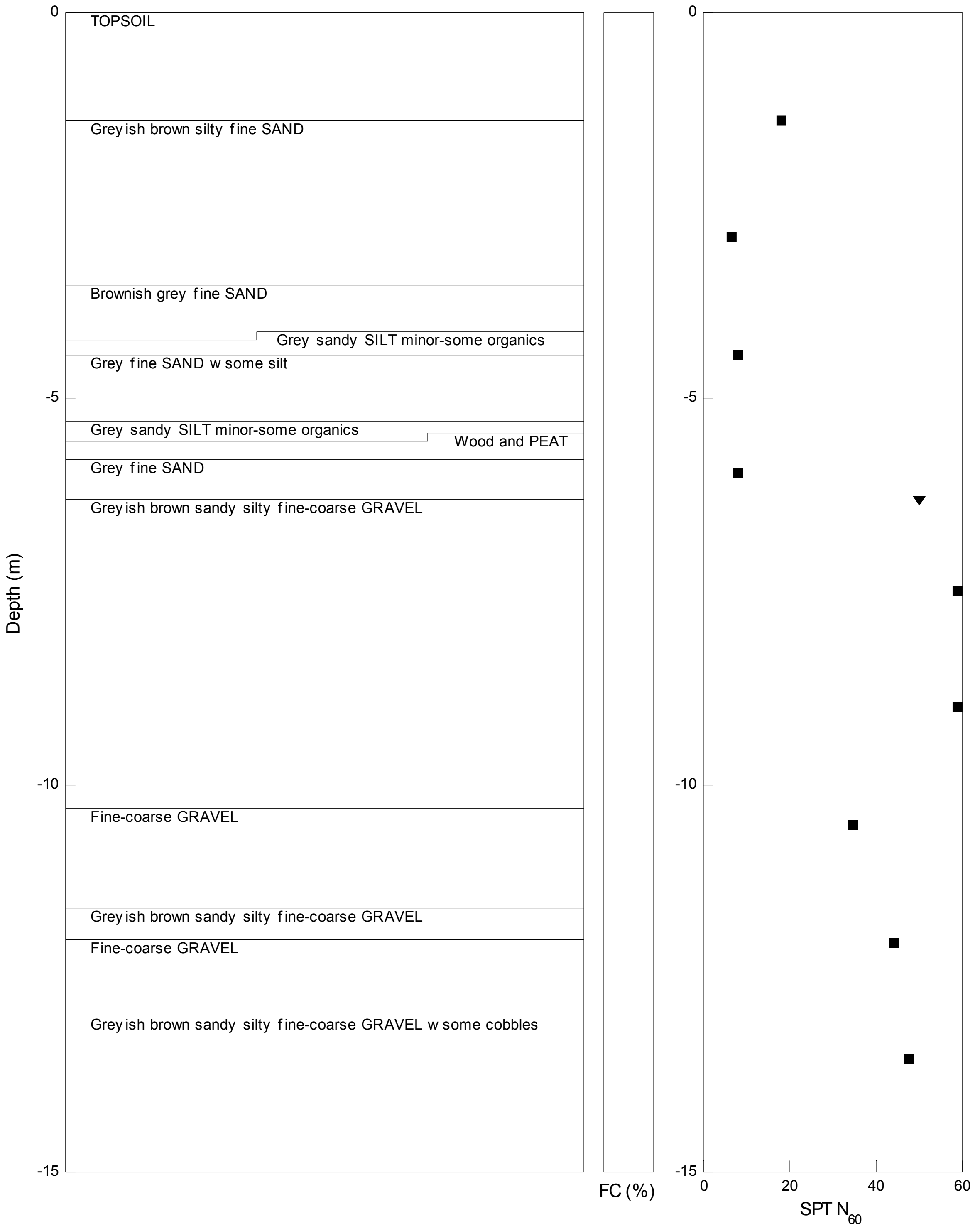
Borehole (RHSC_BH1)

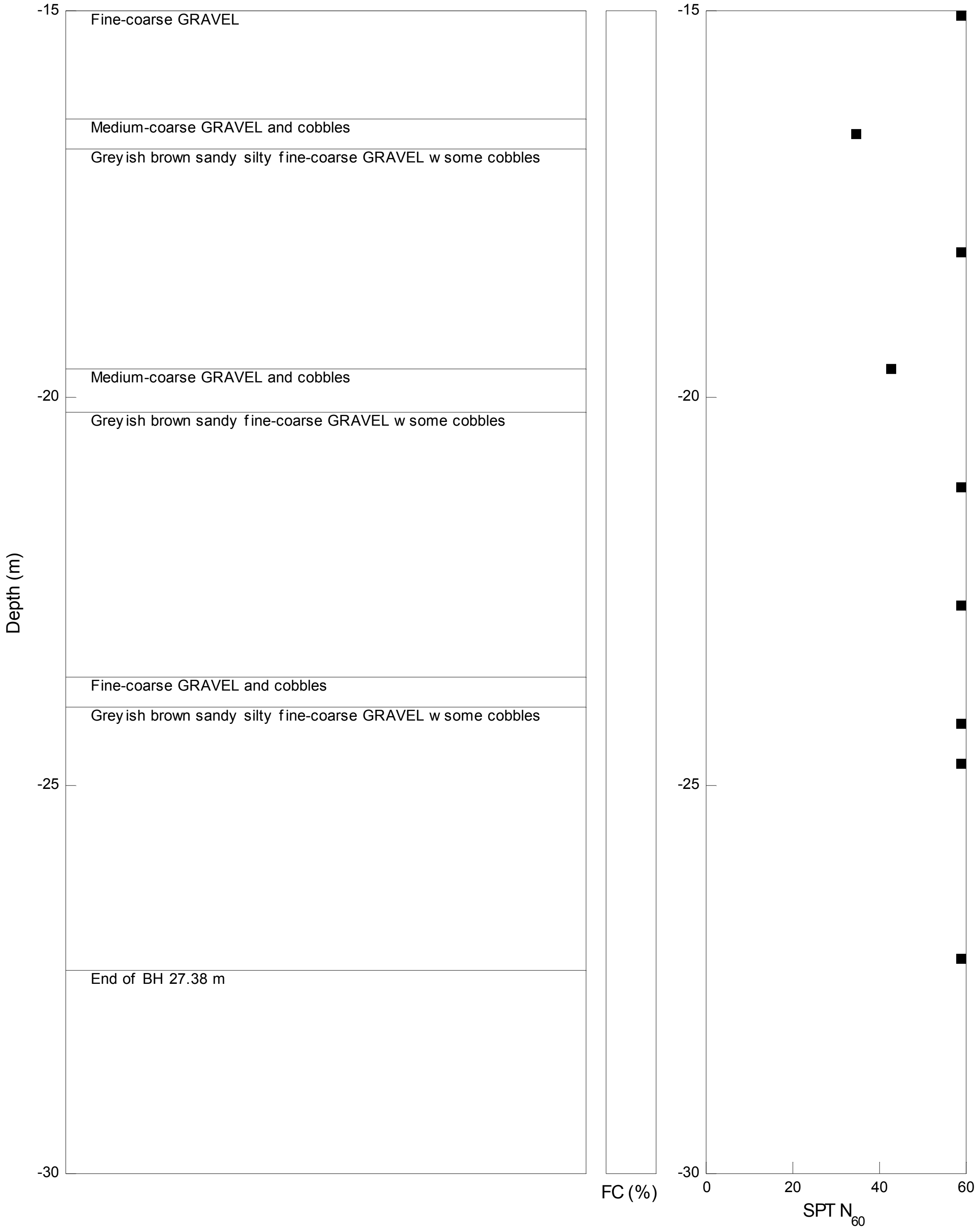
Latitude Longitude (WGS 84): -43.536325 172.564306

Drilling method : Sonic core

Water table depth: 6.4 m

Depth: 27.38 m





Depth (m)
-15
-20
-25
-30
Fine-coarse GRAVEL
Medium-coarse GRAVEL and cobbles
Greyish brown sandy silty fine-coarse GRAVEL w some cobbles
Medium-coarse GRAVEL and cobbles
Greyish brown sandy fine-coarse GRAVEL w some cobbles
Fine-coarse GRAVEL and cobbles
Greyish brown sandy silty fine-coarse GRAVEL w some cobbles
End of BH 27.38 m
FC (%)
0
20
40
60
SPT N60

Shear Wave Profile (RHSC_SW1)

Latitude Longitude (WGS 84): -43.536250 172.563950

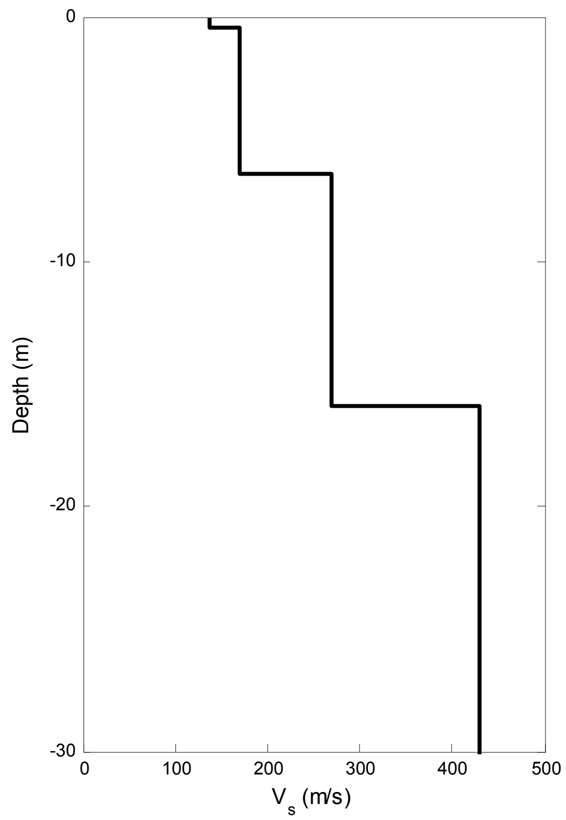
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

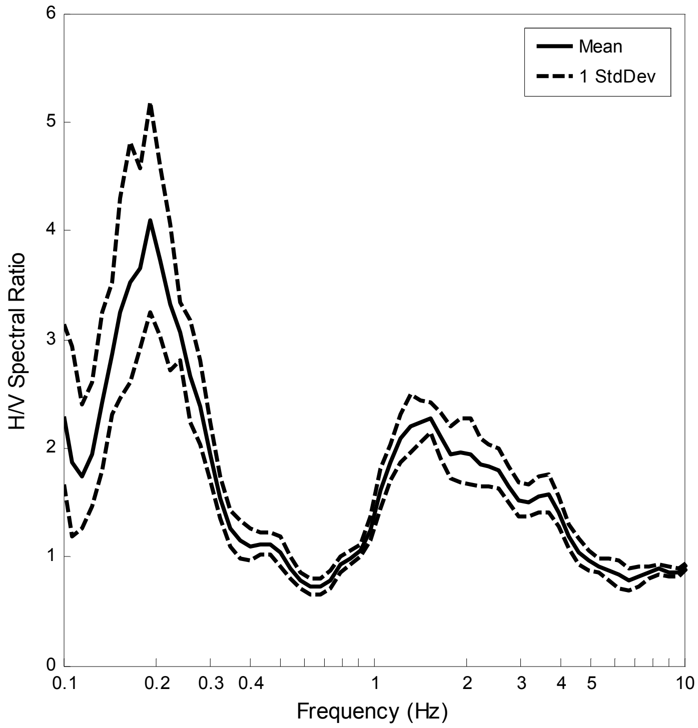
Depth: 31 m



Depth (m)	V_S (m/s)
0.0	137
0.45	170
6.45	270
15.9	430
31.0	

Horizontal-to-vertical (H/V) spectral ratio (RHSC_HV1)

Latitude Longitude (WGS 84):	-43.535770 172.563807
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.15 Shirley Library (SHLC)

Nearby Geotechnical Site Investigation

Table 26 SHLC geotechnical site investigation summary

Investigation Method	Number	Notes
CPT (CPT)	1	
Borehole/SPT (BH)	0	
V_s – surface wave (SW)	1	
H/V Spectral Ratio (HV)	1	

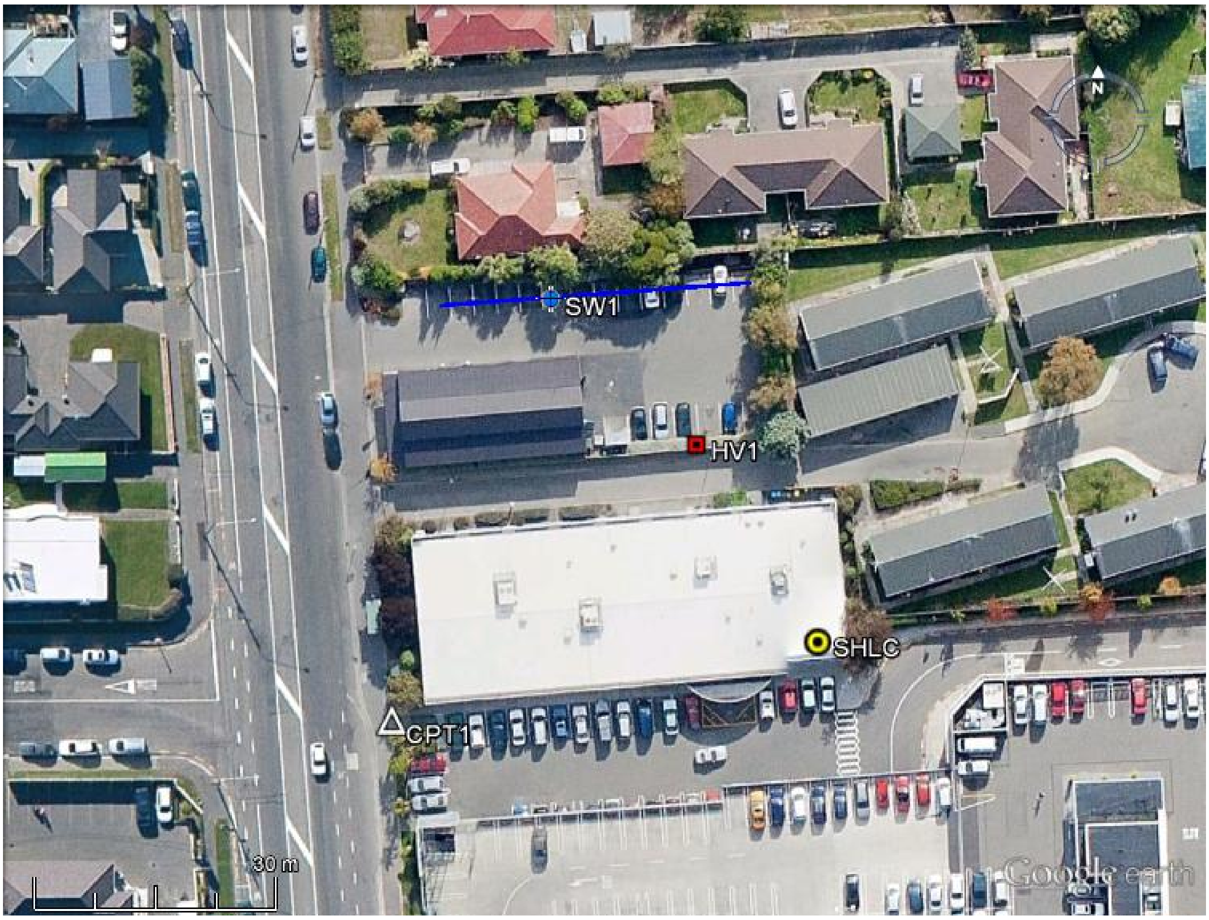


Figure 63 SHLC geotechnical site investigation location plan

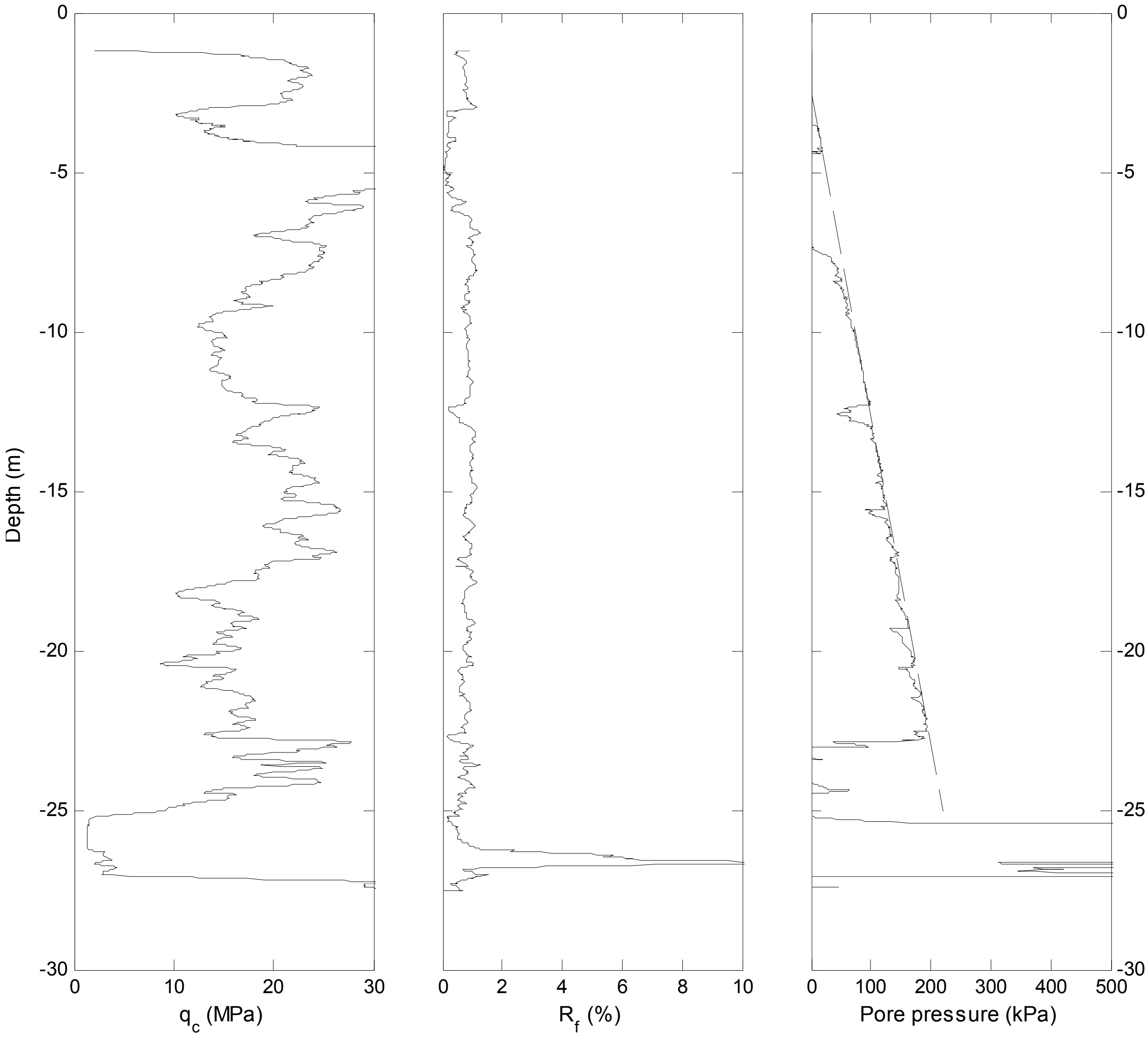
Cone Penetrometer (SHLC_CPT1)

Latitude Longitude (WGS 84): -43.505394 172.662752

Water table depth: 2.6 m

Predrilled: 1.2 m

Depth: 27.58 m



Shear Wave Profile (SHLC_SW1)

Latitude Longitude (WGS 84): -43.504883 172.663000

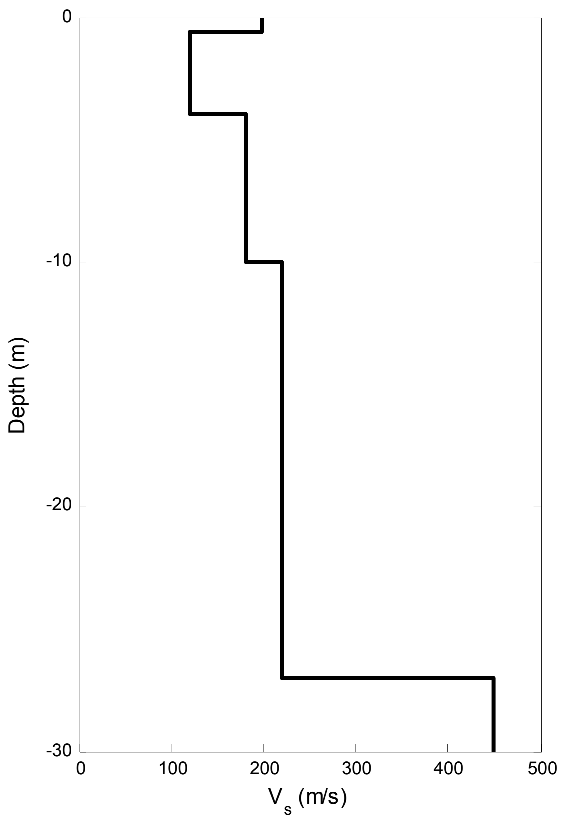
Methods: Active source (MASW, SASW), passive source (linear microtremor array) - Linear array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

Passive source (2D microtremor array) – 16.7 m x 18.2 m L-shaped array of 24 4.5 Hz vertical geophones @ 1.5 m spacing.

MASW Source offsets: 4.6 m, 9.1m, 18.3 m

Source: Minimum of five sledgehammer impacts per offset

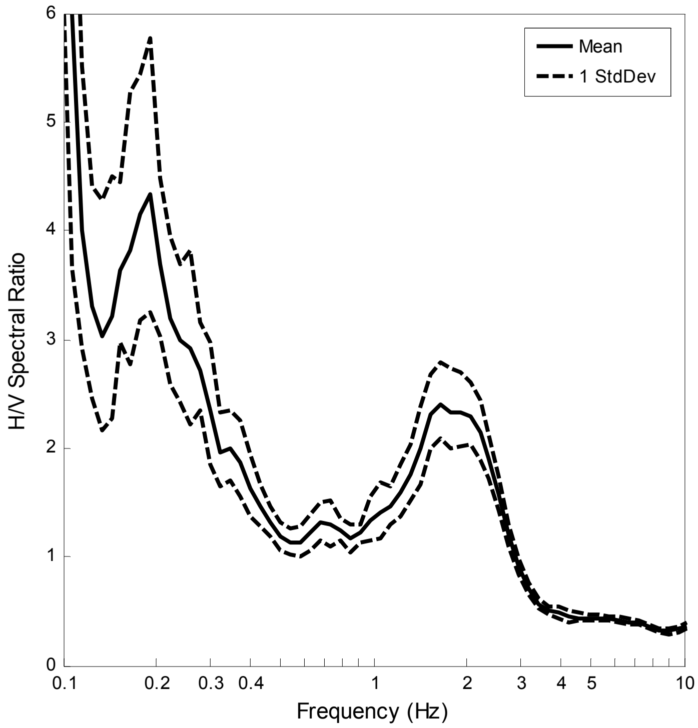
Depth: 35 m



Depth (m)	V_S (m/s)
0.0	198
0.6	121
4.0	180
10.0	220
27.0	450
35.0	

Horizontal-to-vertical (H/V) spectral ratio (SHLC_HV1)

Latitude Longitude (WGS 84):	-43.504955 172.663224
Equipment:	Nanometrics Trillium compact 120 second broadband seismometer
Record length:	1 hour



C.16 Styx Mill Transfer Station (SMTC)

Nearby Geotechnical Site Investigation

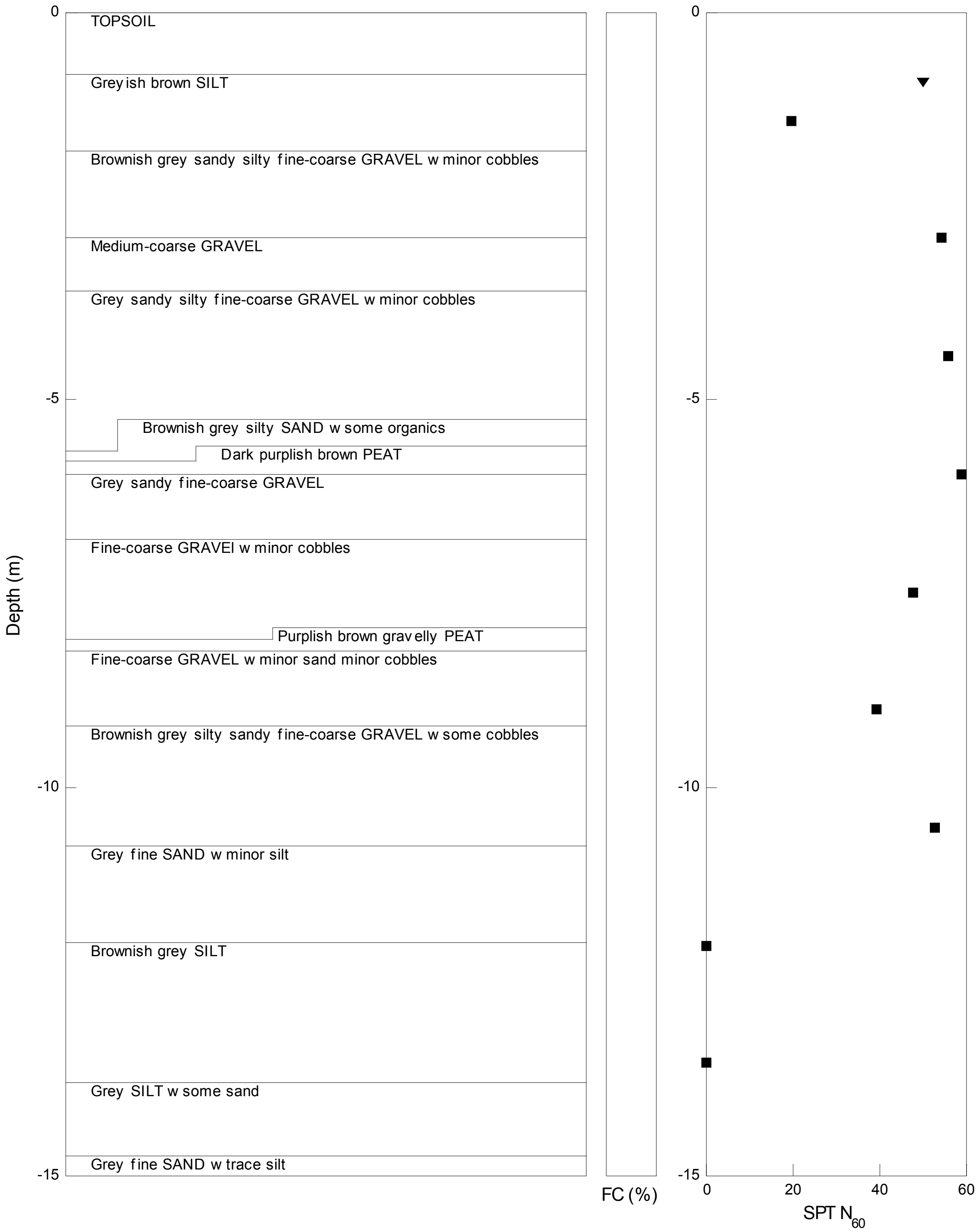
Table 27 SMTC geotechnical site investigation summary

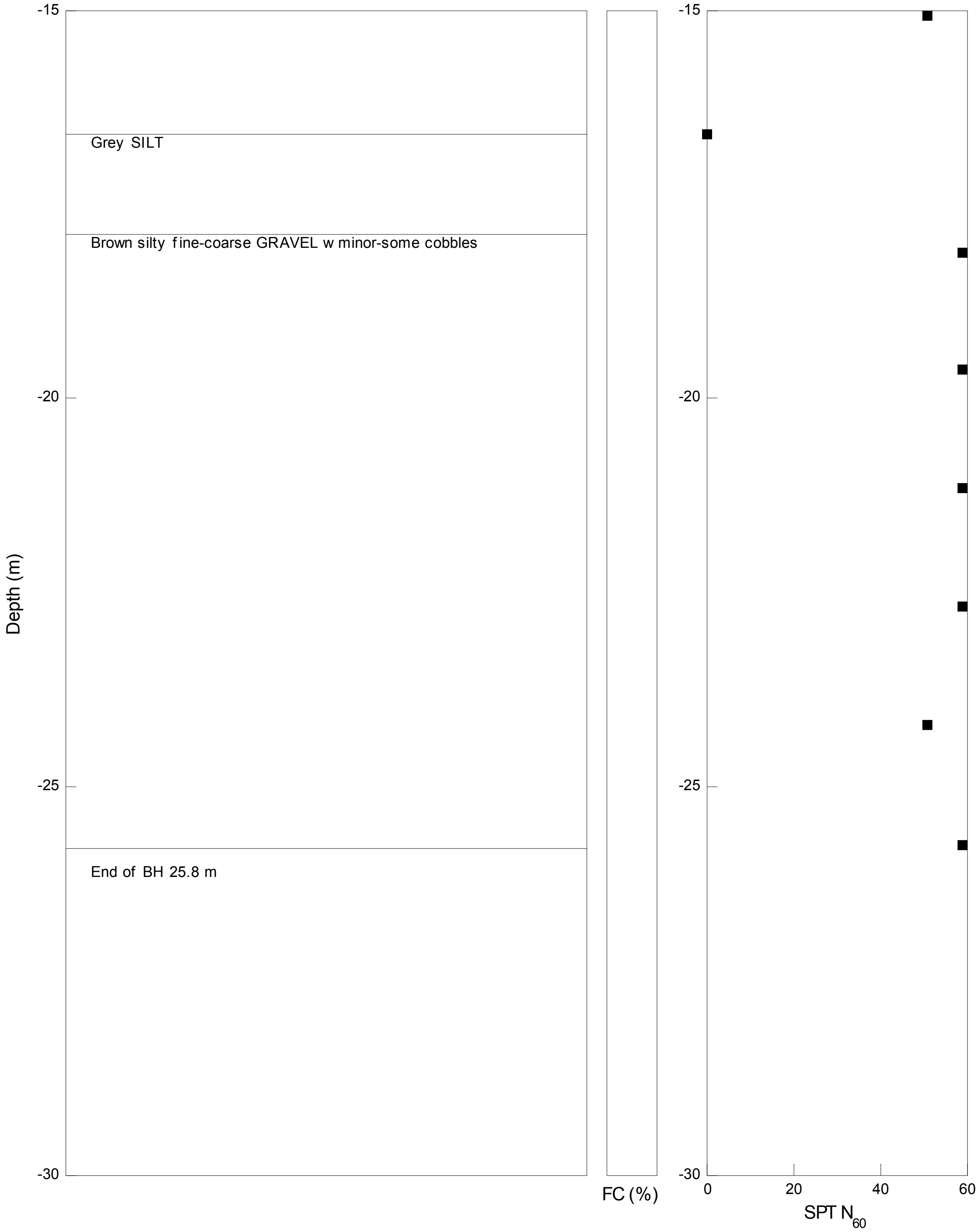
Investigation Method	Number	Notes
CPT (CPT)	0	Gravelly site
Borehole/SPT (BH)	1	
V_s – surface wave (SW)	1	
H/V (HV)	1	

Figure 64 SMTC geotechnical site investigation location plan

Borehole (SMTC_BH1)

Latitude Longitude (WGS 84):	-43.467097 172.613192
Drilling method :	Sonic core
Water table depth:	1.0 m
Depth:	25.8 m

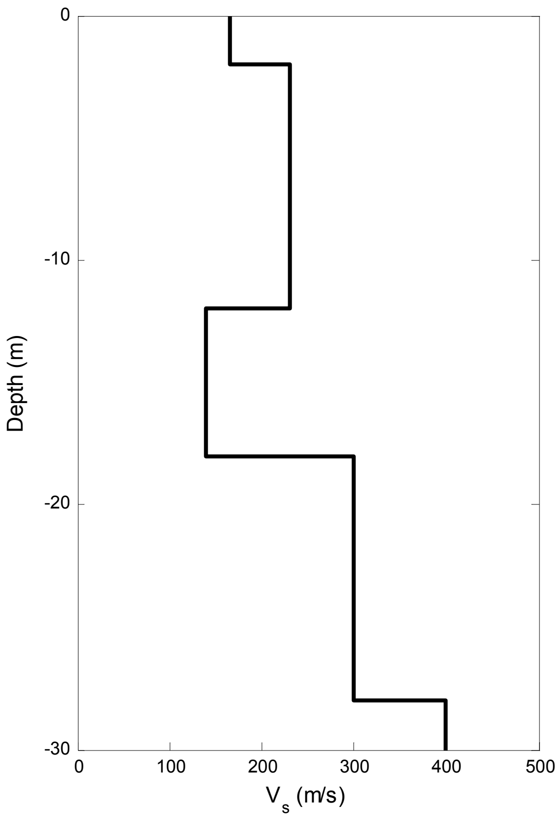




-15
-20
-25
-30
Grey SILT
Brown silty fine-coarse GRAVEL w minor-some cobbles
End of BH 25.8 m
Depth (m)
FC (%)
0
20
40
60
SPT N_{60}

Shear Wave Profile (SMTC_SW1)

Latitude Longitude (WGS 84):	-43.467033 172.613100
Methods:	Active source (MASW, SASW) - Linear array of 24 4.5 Hz vertical geophones @ 2 m spacing.
MASW Source offsets:	5.0 m, 10 m, 20 m
Source:	Minimum of ten sledgehammer impacts per offset
Depth:	30 m



Depth (m)	V_S (m/s)
0.0	130
2.0	195
6.0	230
12.0	120
14.8	170
16.7	120
18.0	400
28.0	500
30.0	

Horizontal-to-vertical (H/V) spectral ratio (SMTC_HV1)

Latitude Longitude (WGS 84): -43.467078 172.613124

Equipment: Nanometrics Trillium compact 120 second broadband seismometer

Record length: 1 hour